High-Precision Experiments Using Radioactive Ions, Lasers and/or Storage Devices

- for nuclear physics and atomic physics

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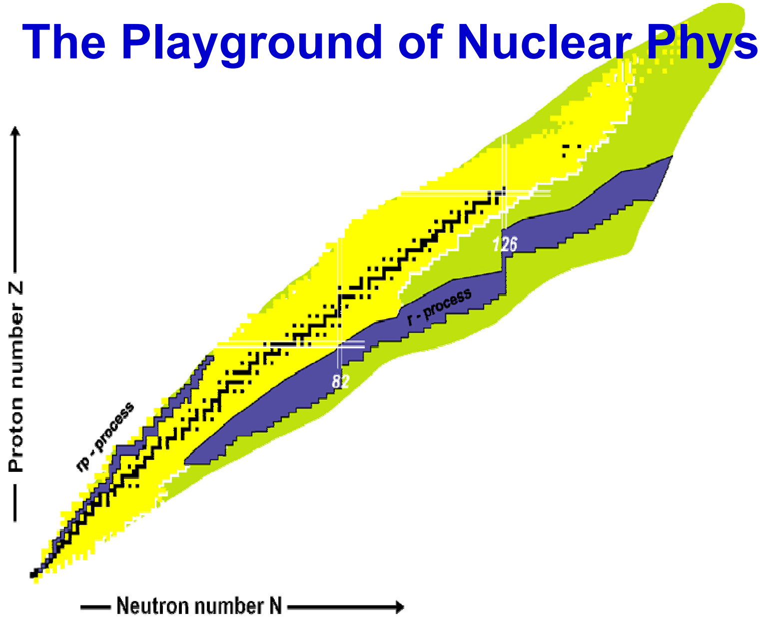
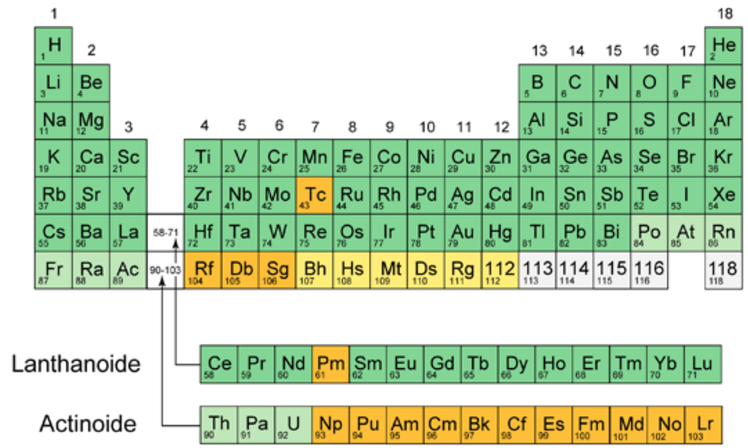
Outline

1. What can we learn on nuclear ground state properties from optical spectroscopy?
2. Optical & trapping techniques
3. Extending the area of investigated isotopes
4. A plea to foresee the installation of a laser ion source and for further development of the laser ion source trap (LIST)
5. Highly charged ions (HCI)
   - test of QED in HCI
   - fundamental constants (m_e, α)
   - nuclear charge properties
   - decay of polarized nuclei
6. Conclusion

The Playground of Nuclear Physics



The Playground of Atomic Physics



Nuclear Ground State Properties by Atomic-Physics Techniques

* **MASS** — nuclear binding energy

* **NUCLEAR HALF-LIFE** — decay rates

* **HYPERFINE STRUCTURE**

  1. Hyperfine Interaction
     $J + I = F$ — nuclear spin

  2. Magnetic Dipole HFS
     $A = \mu_I \langle H(0) \rangle / I\,J$ — nuclear magnetic moment

  3. Hyperfine anomaly
     ${}^1\Delta^2 = \{(A_1/g_1)/(A_2/g_2)\} - 1$ — change of distribution of nuclear magnetism between two isotopes

  4. Electric Quadrupole HFS
     $B = e_0\, Q_s \langle \varphi_{zz}(0) \rangle$ — spectroscopic quadrupole moment

* **ISOTOPE SHIFT**
  Finite Size Effect
  $\delta \langle r^2 \rangle^{A,A'}$ — change of ms charge radius

Nuclear Ground State Properties by Atomic-Physics Techniques

* **MASS** — **nuclear binding energy**

* **NUCLEAR HALF LIFE**

This information is model-independent.

$J + I = F$ — **nuclear spin**

This information is the most basic one and should be known for each nucleus.

${}^{1}\Delta^{2} = \{(A_1/g_1)/(A_2/g_2)\} - 1$ — **magnetism between two isotopes**

Presently, only optical isotope shift measurements give access to the charge radii of radionuclides.

* **ISOTOPE SHIFT**

Finite Size Effect

$\delta \langle r^2 \rangle^{A,A'}$ — **change of ms charge radius**

The Minima of the Energy-Deformation Curve can be Determined by Atomic-Physics Techniques

mass $\Rightarrow$ depth of minima

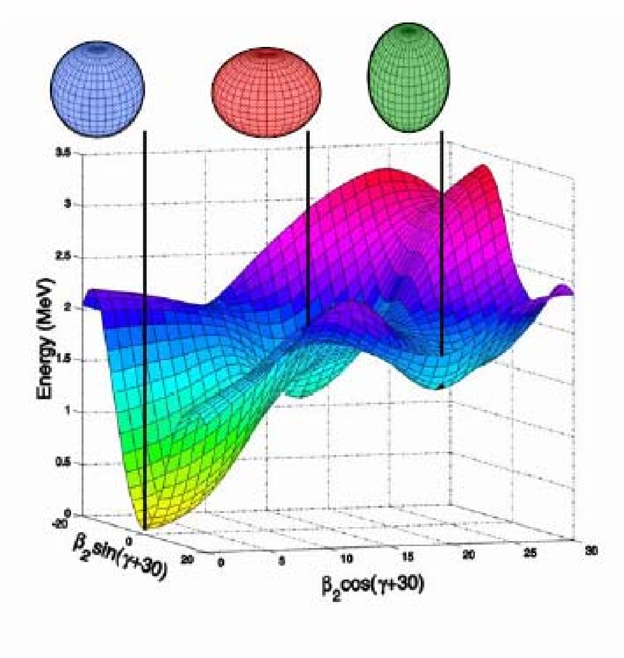
isotope shift $\rightarrow |\beta^2|$ $\Rightarrow$ size of deformation

isomer shift $\rightarrow \delta|\beta^2|$ $\Rightarrow$ difference in deformation

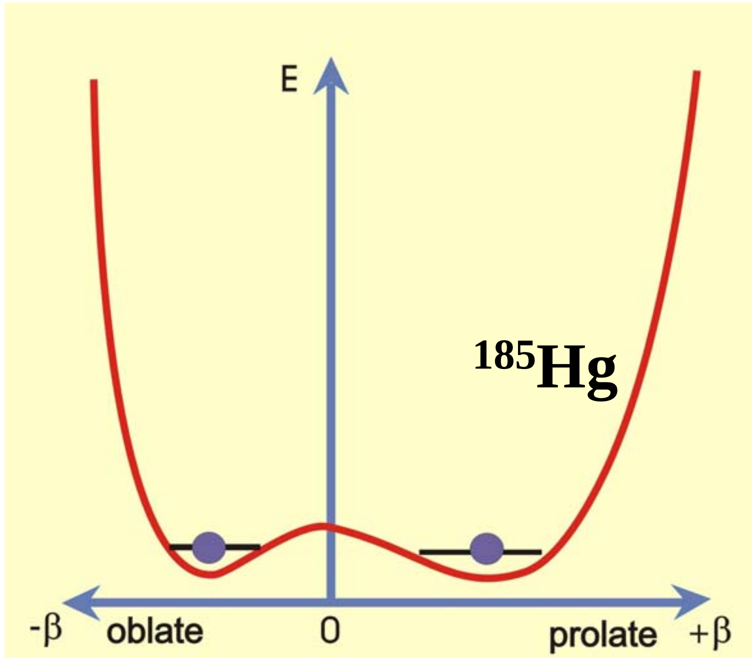
quadrupole moment $\Rightarrow$ sign of deformation

spin $\Rightarrow$ } single-particle properties

magnetic moment $\Rightarrow$ }



Potential Energy Surface for ^{186}Pb

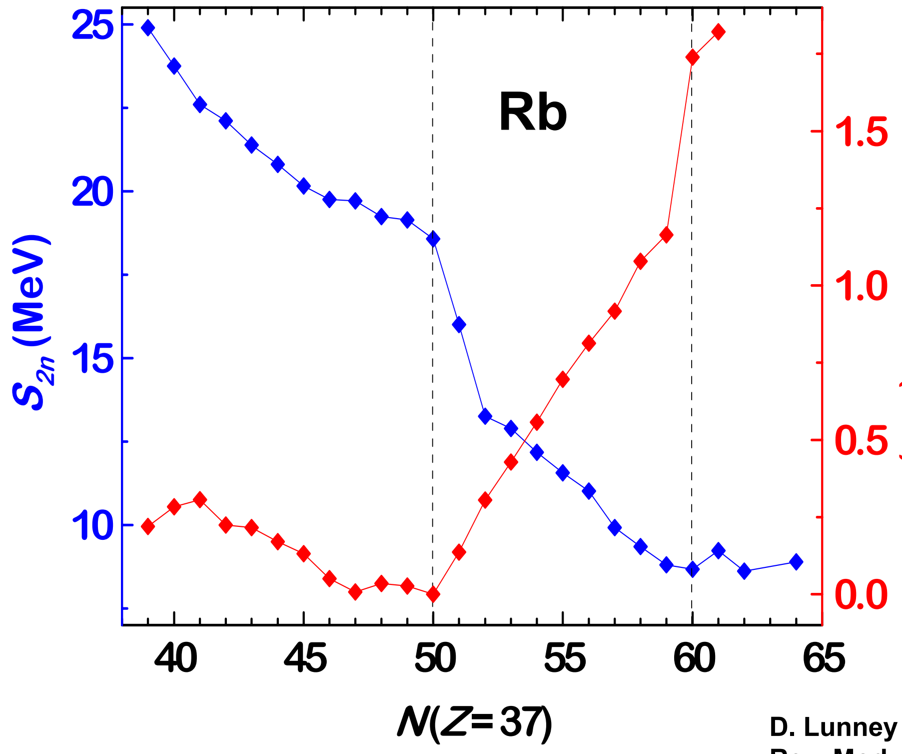


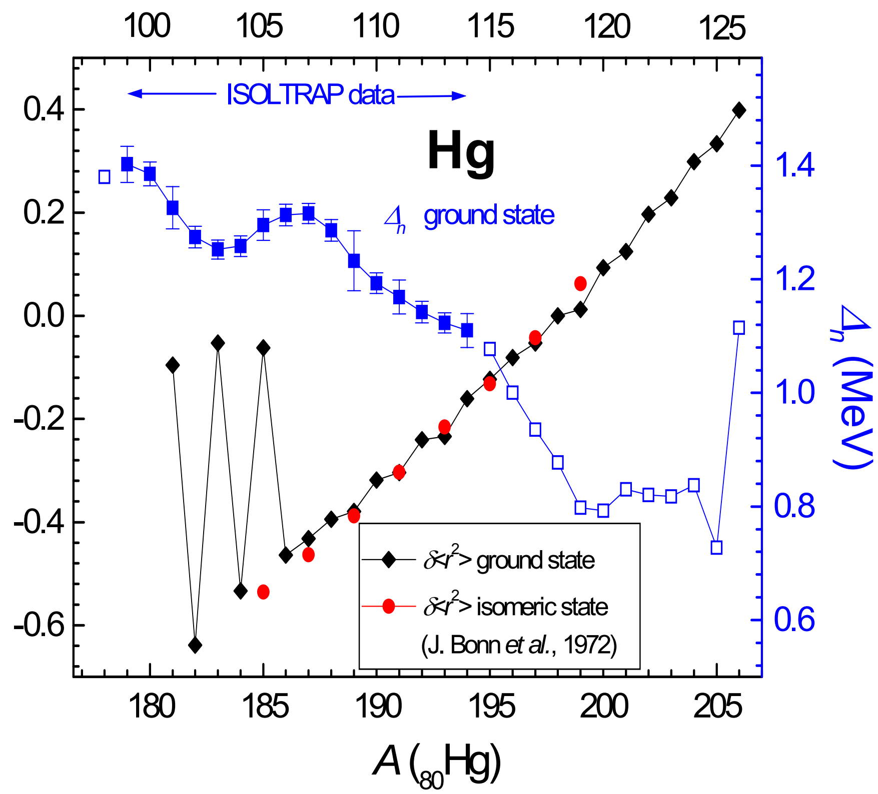
A. Andreyev et al., Nature 405 (2000) 430

Comparison: Charge Radii – Nuclear Binding Energies

The sensitivity of mass spectrometry and optical spectroscopy (spin, moments, charge radii) to nuclear structure effects.

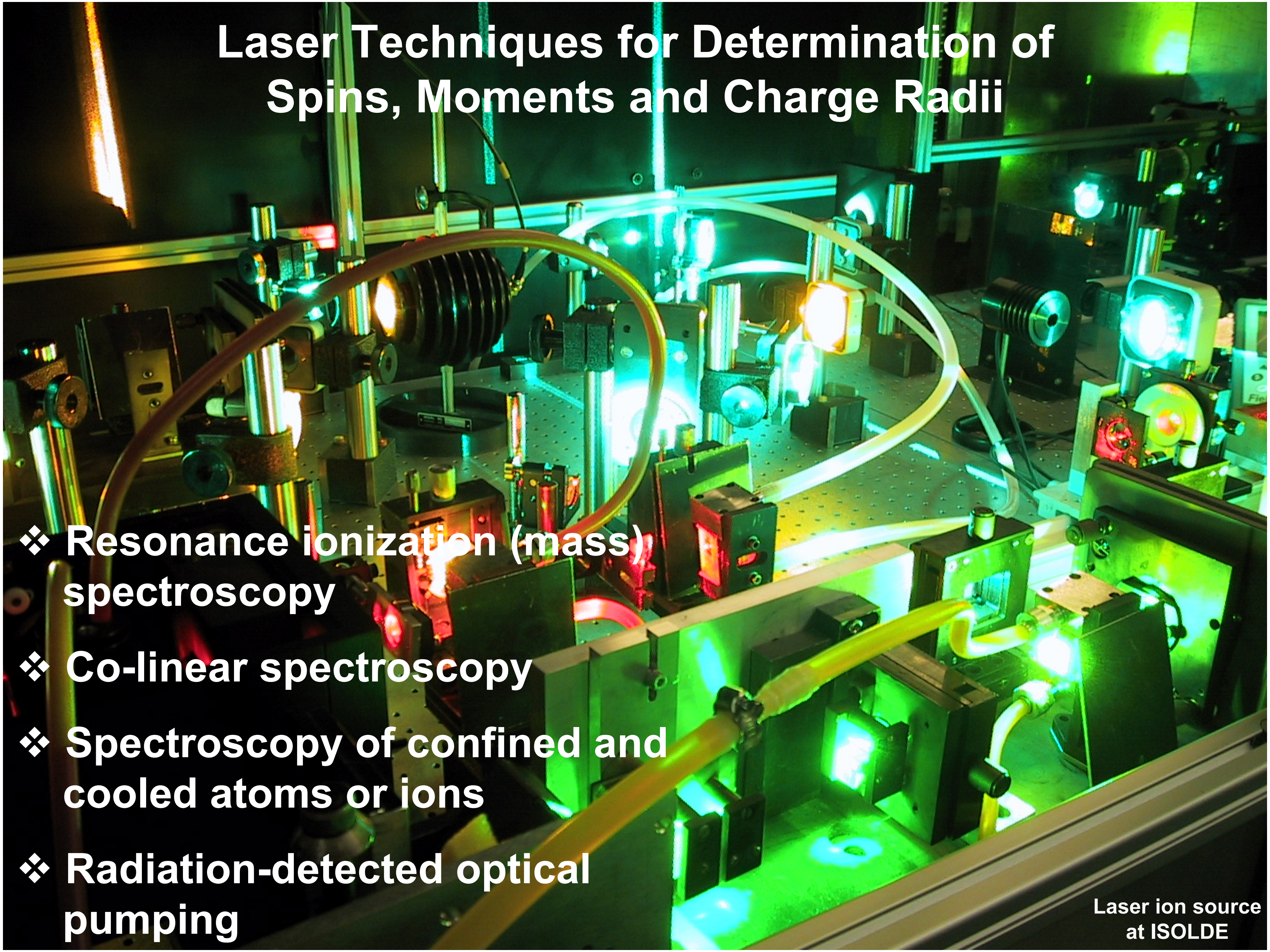
Examples : Charge radii of Rb and Hg isotopes versus mass information





D. Lunney et al.
Rev. Mod. Phys. 75 (2003) 1021

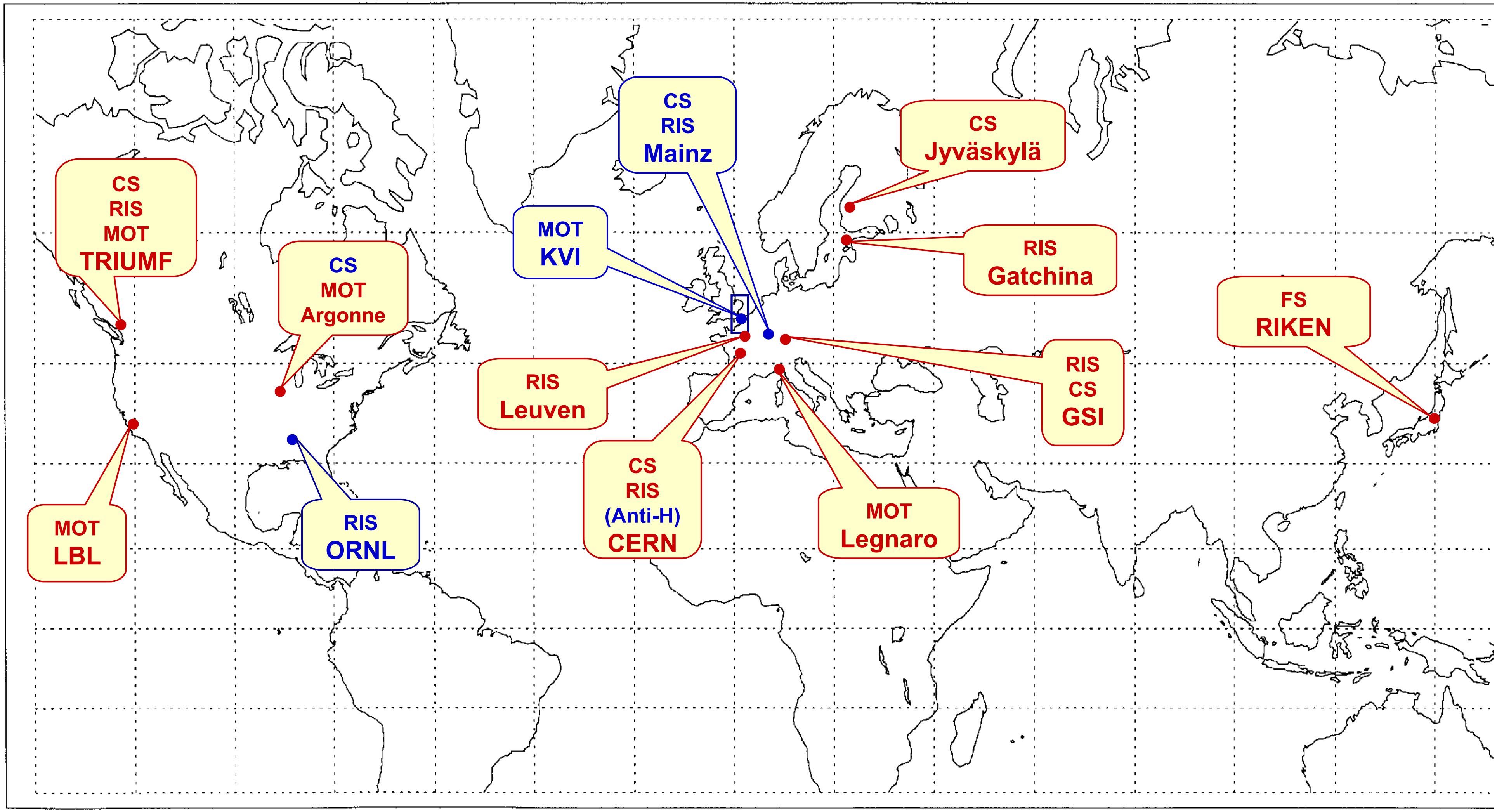
Laser Techniques for Determination of Spins, Moments and Charge Radii



- Resonance ionization (mass) spectroscopy
- Co-linear spectroscopy
- Spectroscopy of confined and cooled atoms or ions
- Radiation-detected optical pumping

Laser ion source at ISOLDE

Laser Spectroscopy of Radionuclides at Accelerators or Reactors



• operating facilities • facilities under construction or test

How Sensitive is Optical Spectroscopy?

$\sigma_{\text{photon absorption}} \approx \lambda^2_{\text{photon}} \approx 10^{-10}\ \text{cm}^2 = 10^{14}\ \text{barn}$

$\Rightarrow$ useful thickness of target: < 10^{10} atoms/cm^2 or < 1pg/cm^2

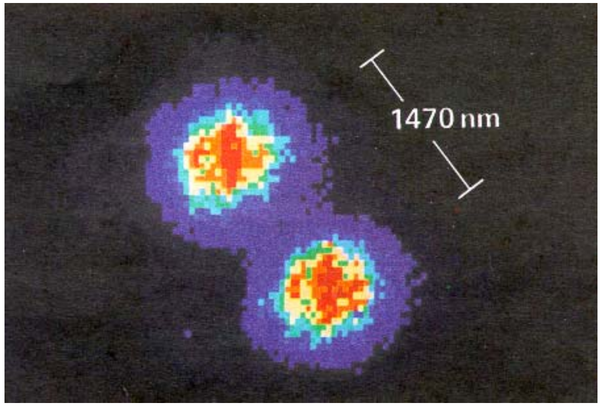
power of tunable cw dye laser ≈ 100 mW … 1 W

$\Rightarrow$ flux of photons ≈ 10^{17} … $10^{18}/(s\cdot cm^2)$ $\Rightarrow$ up to 10^8 excitation/(s·atom)

"in principle" only 1 atom sufficient

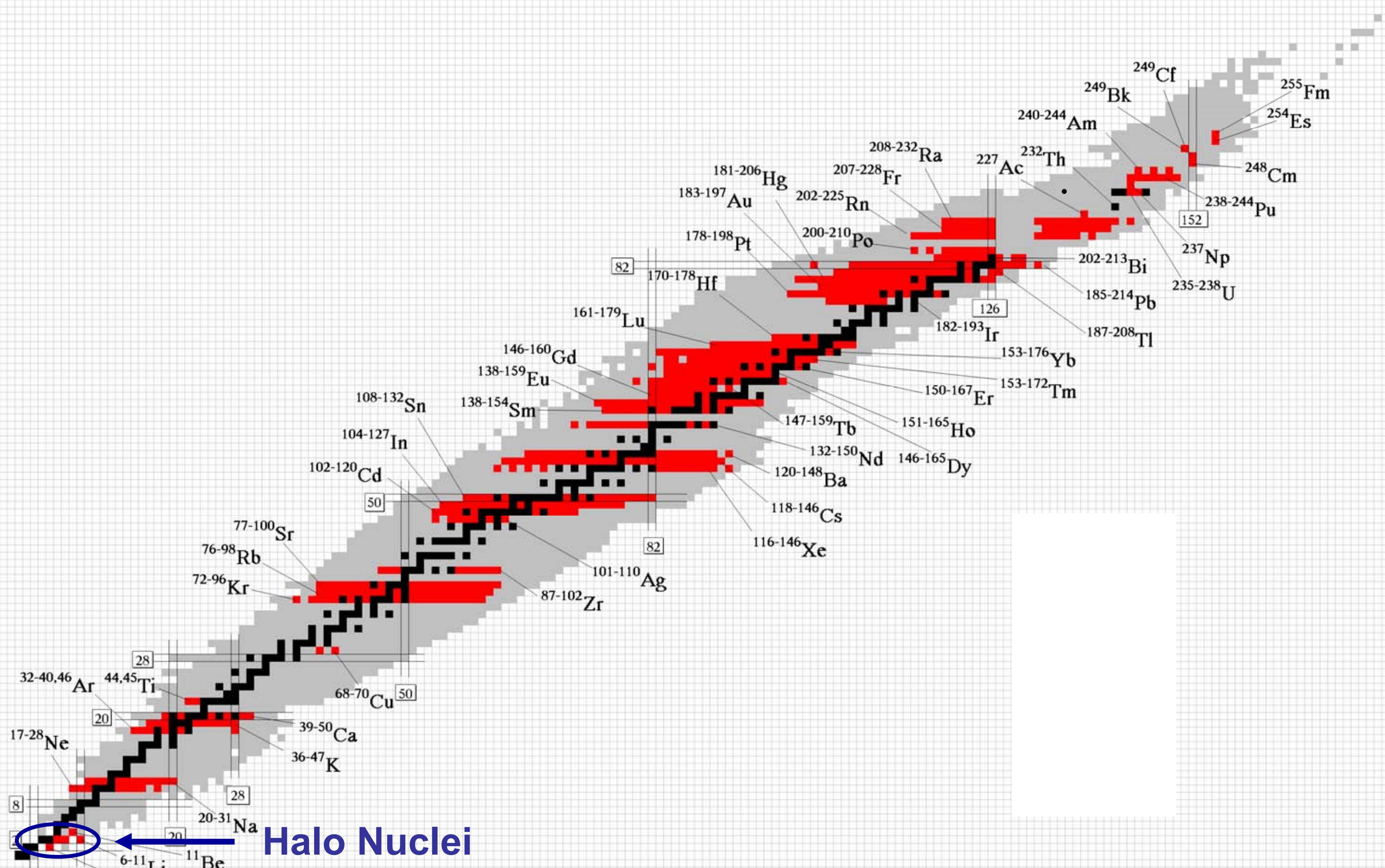
First demontrarion: Ba^+ stored in an ion trap

(Toschek, Dehmelt, Neuhauser et al.)



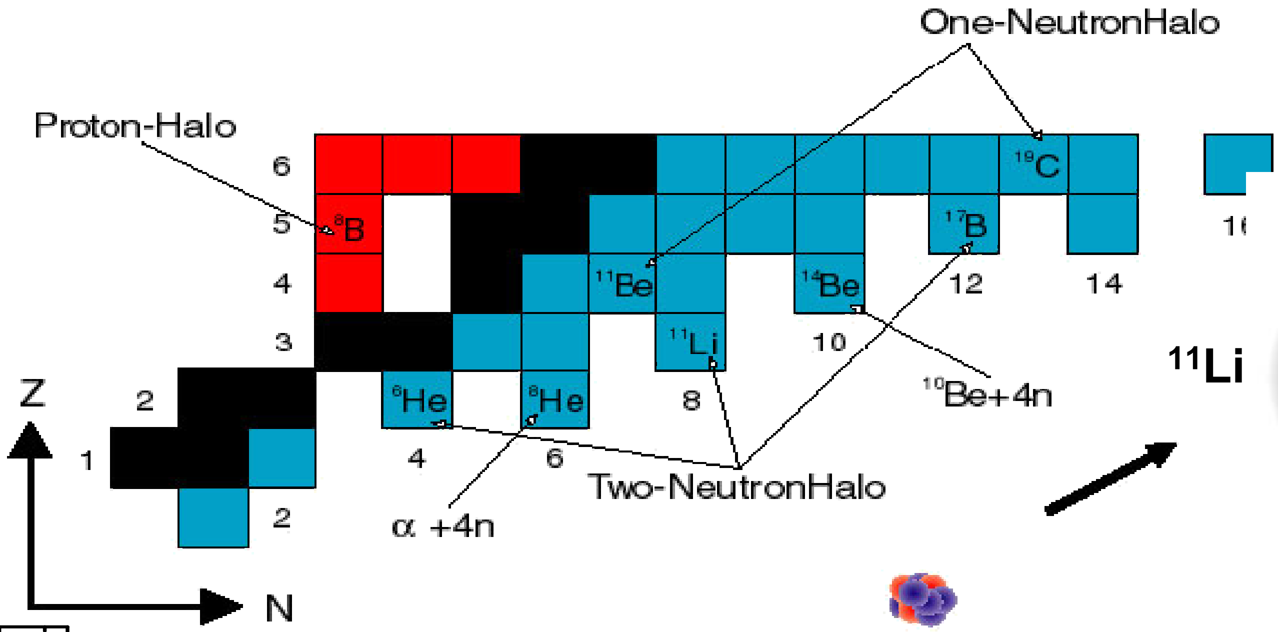
R.G.Voe et al., PRL 76 (1996) 2049

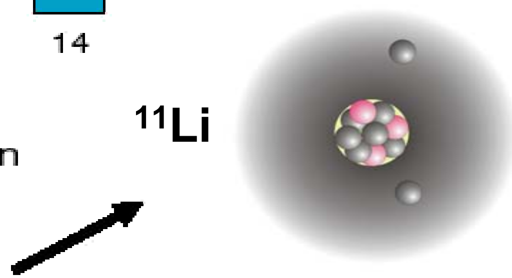
Laser Spectroscopy of Light Elements

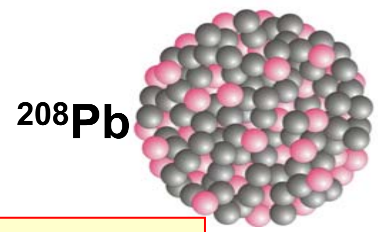


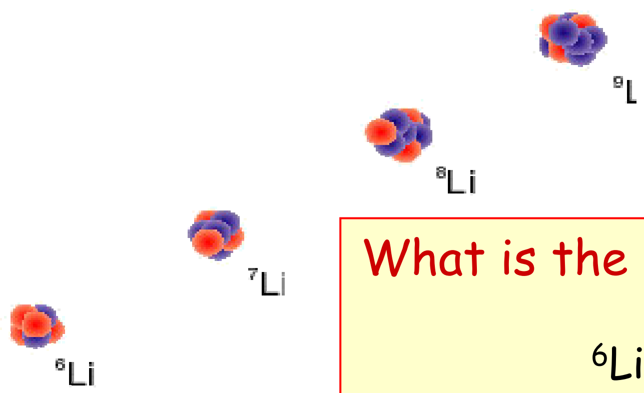
H.-J. Kluge and W. Nörtershäuser, Spectrochim. Acta B, 58 (2003).

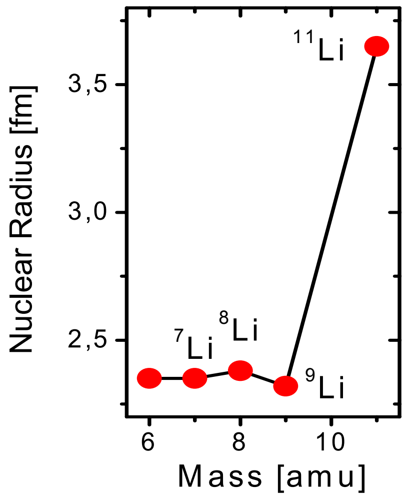
Nuclear Charge Radii of Halo Nuclei











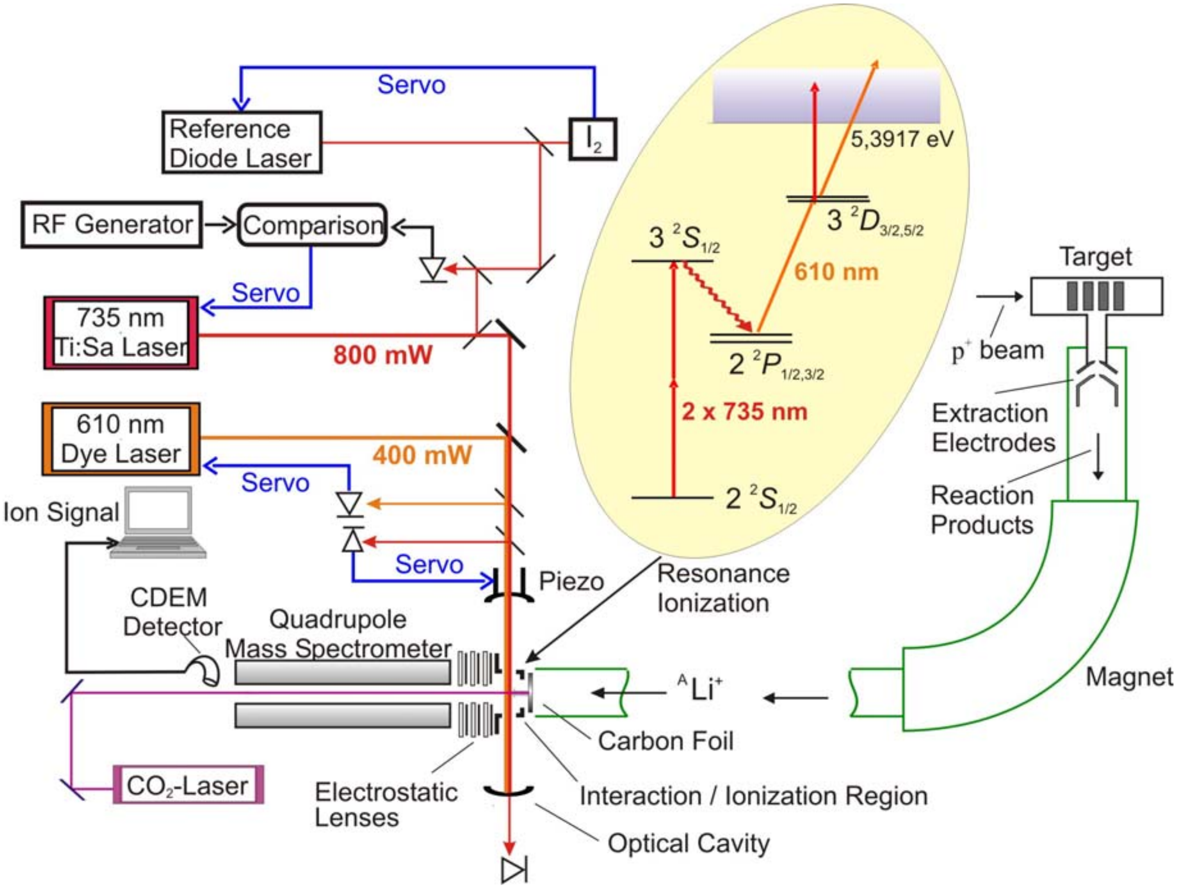
I. Tanihata et al.

What is the charge radius ?

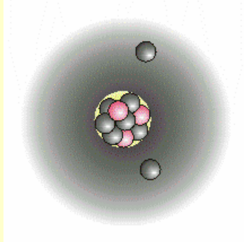
^{6}Li – ^{7}Li:
mass shift ≈ 11 GHz
volume shift ≈ 1 MHz

Yan, Z.-C. and G.W.F. Drake, PRA 66, 042504 (2002)

Doppler-Free Resonance Ionization Mass Spectroscopy of Lithium Isotopes at GSI and TRIUMF



^{11}Li



Lifetime ≈ 9 ms
30,000 Atoms/s

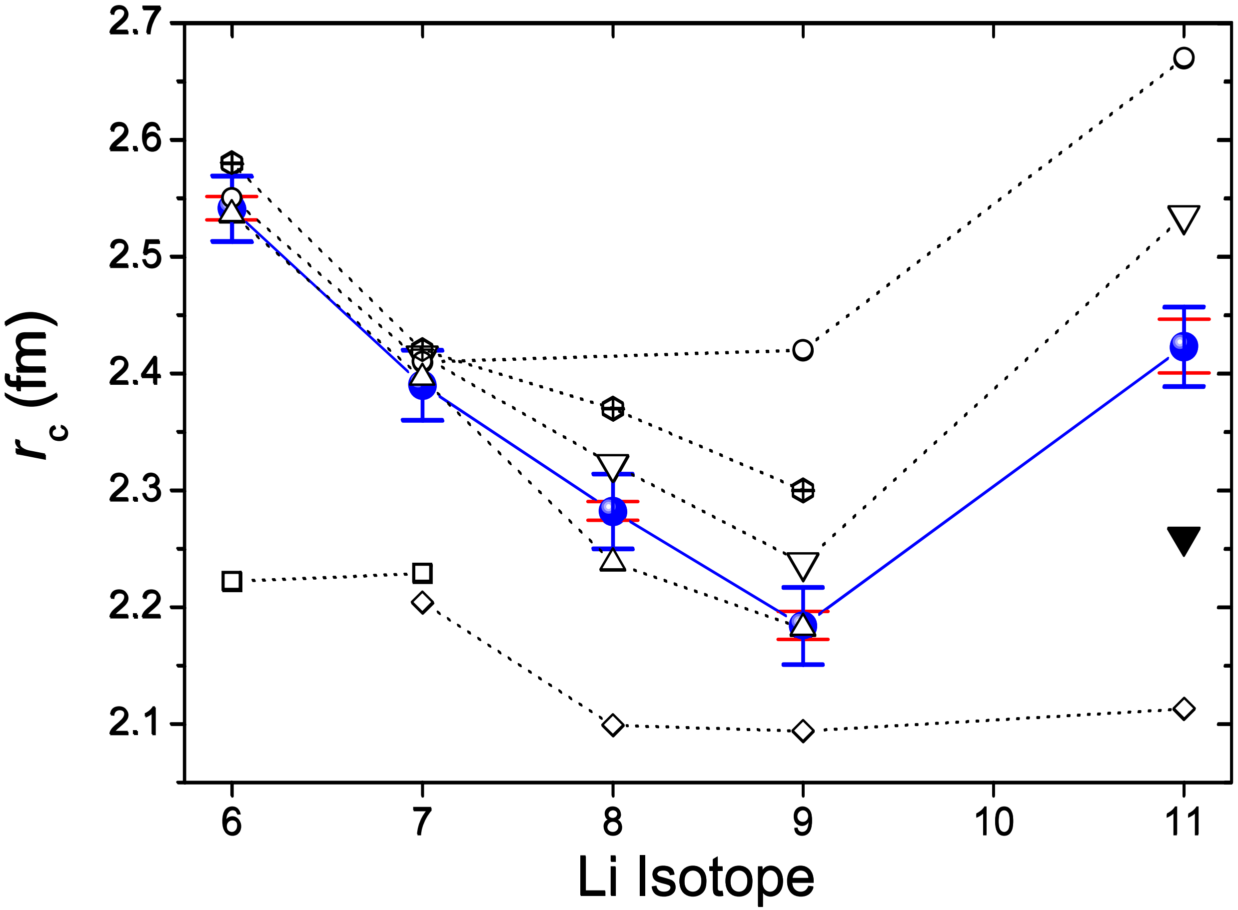
Novel technique developed at GSI by Wilfried Nörtershäuser, Andreas Dax et al.

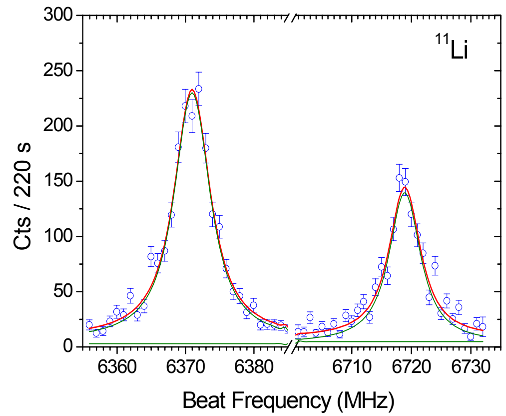
^{8,9}Li at GSI
^{11}Li at TRIUMF

A relative accuracy of better than 10^{-5} is required for the IS measurement **and** for the calculation of the mass shift.

Mass shift calculation by G. Drake, Z.-C. Yan, K. Pachucki et al.

Nuclear Charge Radii of Lithium Isotopes





Experiment

Isotope Shift (this experiment, 2004)

Theory

ab initio No-Core Shell Model

Large-Basis Shell Model (P. Navrátil 2003, 1998)

Greens-Function Monte Carlo (S. C. Pieper 2001/2002)

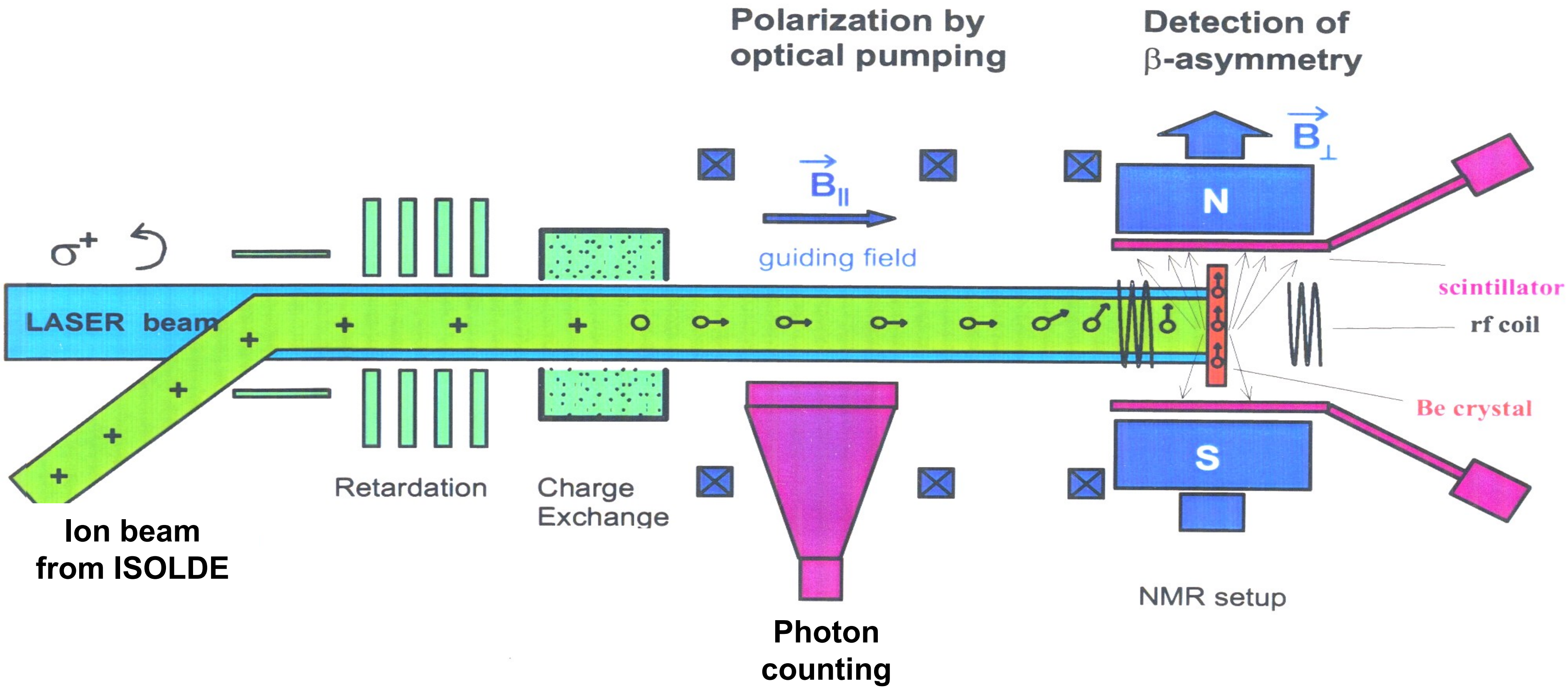
Stochastic Variational Multi Cluster (Y. Suzuki, 2002)

Fermionic Molecular Dynamics (T. Neff, 2005)

Dynamic Correlation Model (M. Tomaselli, 2002)

R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
M. Puchalski *et al.*, PRL 97, 133001 (2006)

Colinear Spectroscopy Combined with Nuclear Radiation Detected Pumping of Lithium-11 at ISOLDE

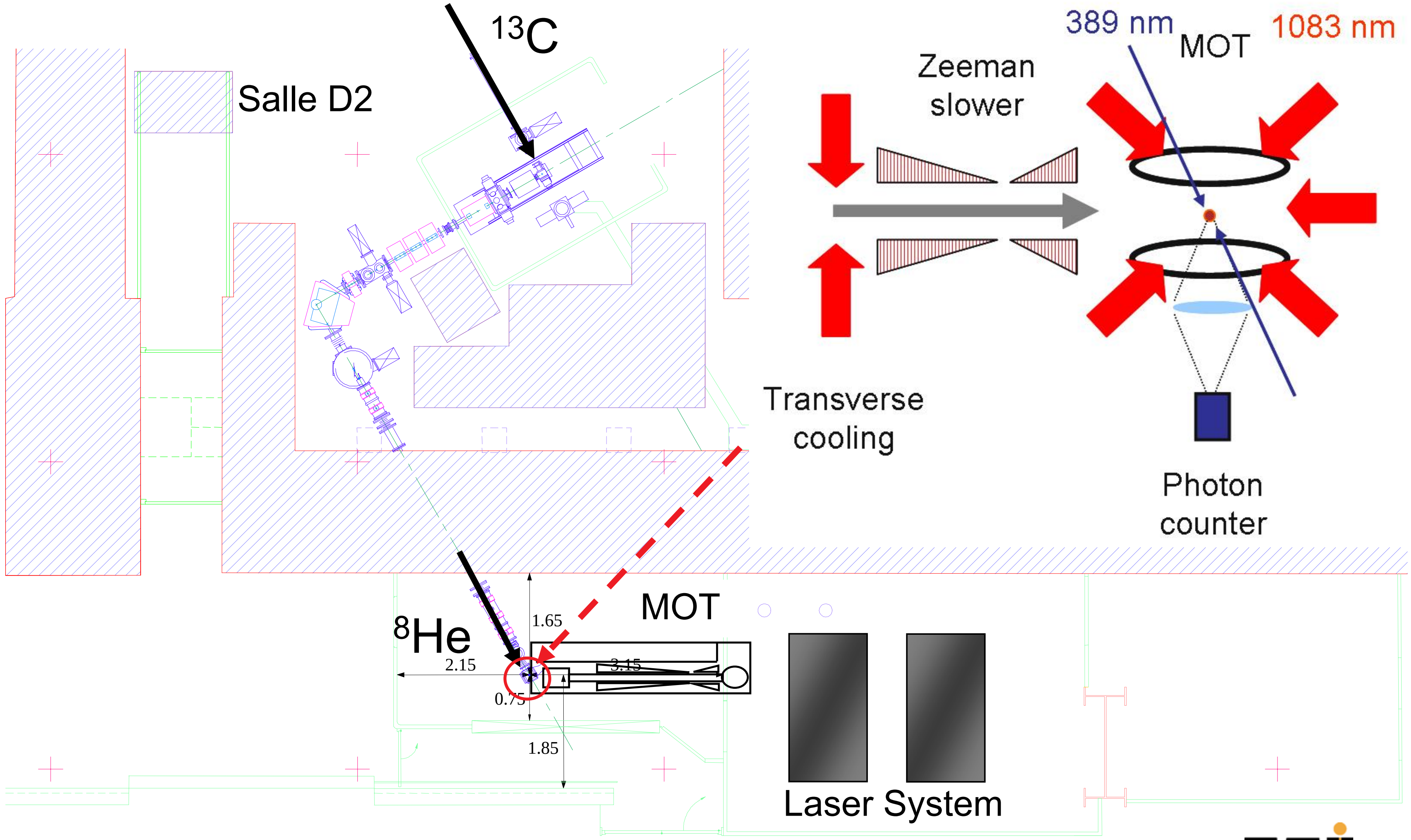


Spin & magnetic moment : E. Arnold et al., PL B 197 (1987) 311

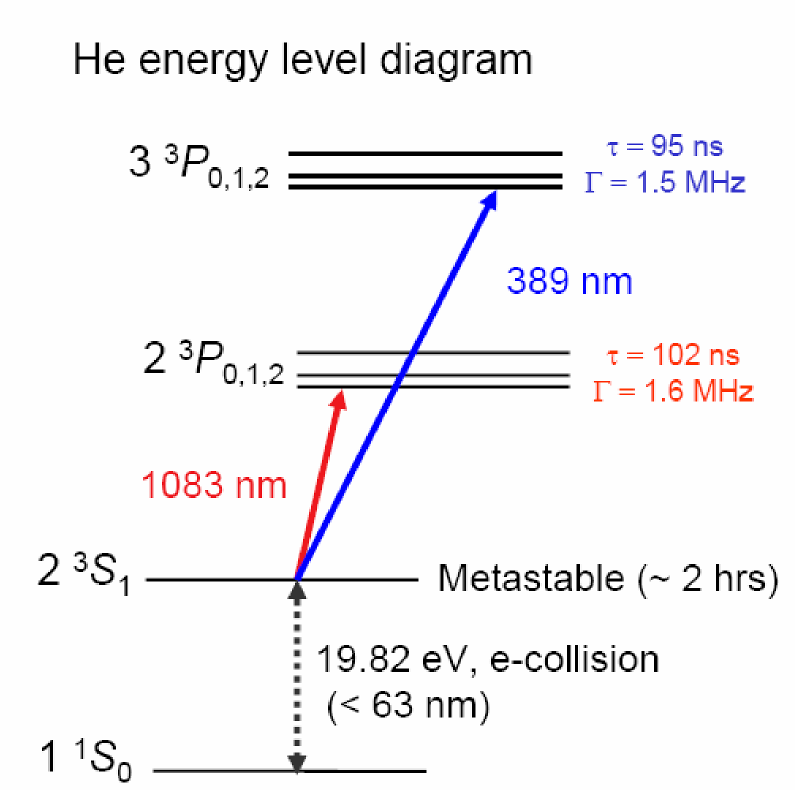
Spectroscopic quadrupole moment: First round: E. Arnold et al., PL B 281 (1992) 16

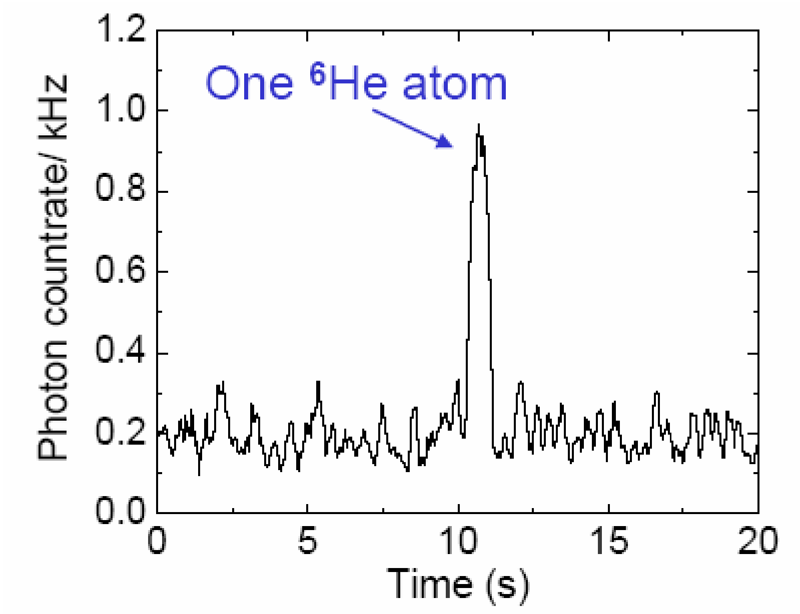
Second round: R. Neugart, G. Neyens et al. (to be published)

Set-up for Determination of the Charge Radius of Helium-8 at GANIL



Detection of a Single ^{6}He Atom at Argonne





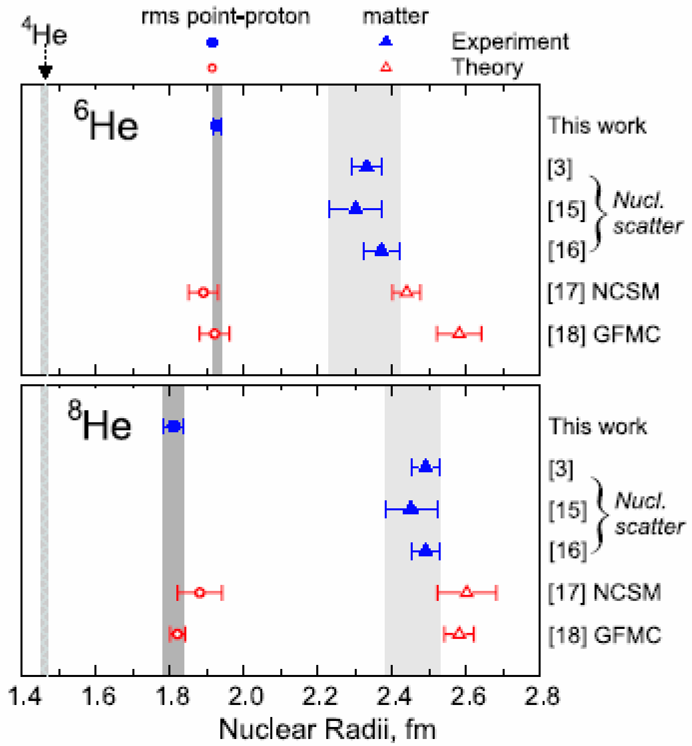
Capture efficiency: ~ 10^{-8} → single atom detection necessary!
Single-atom signal: ~ 1.0 kHz
Single-atom S/N: ~ 10 in 100 ms
^{6}He capture rate: ~ 150 per hour

Nuclear Charge Radius of Helium-8

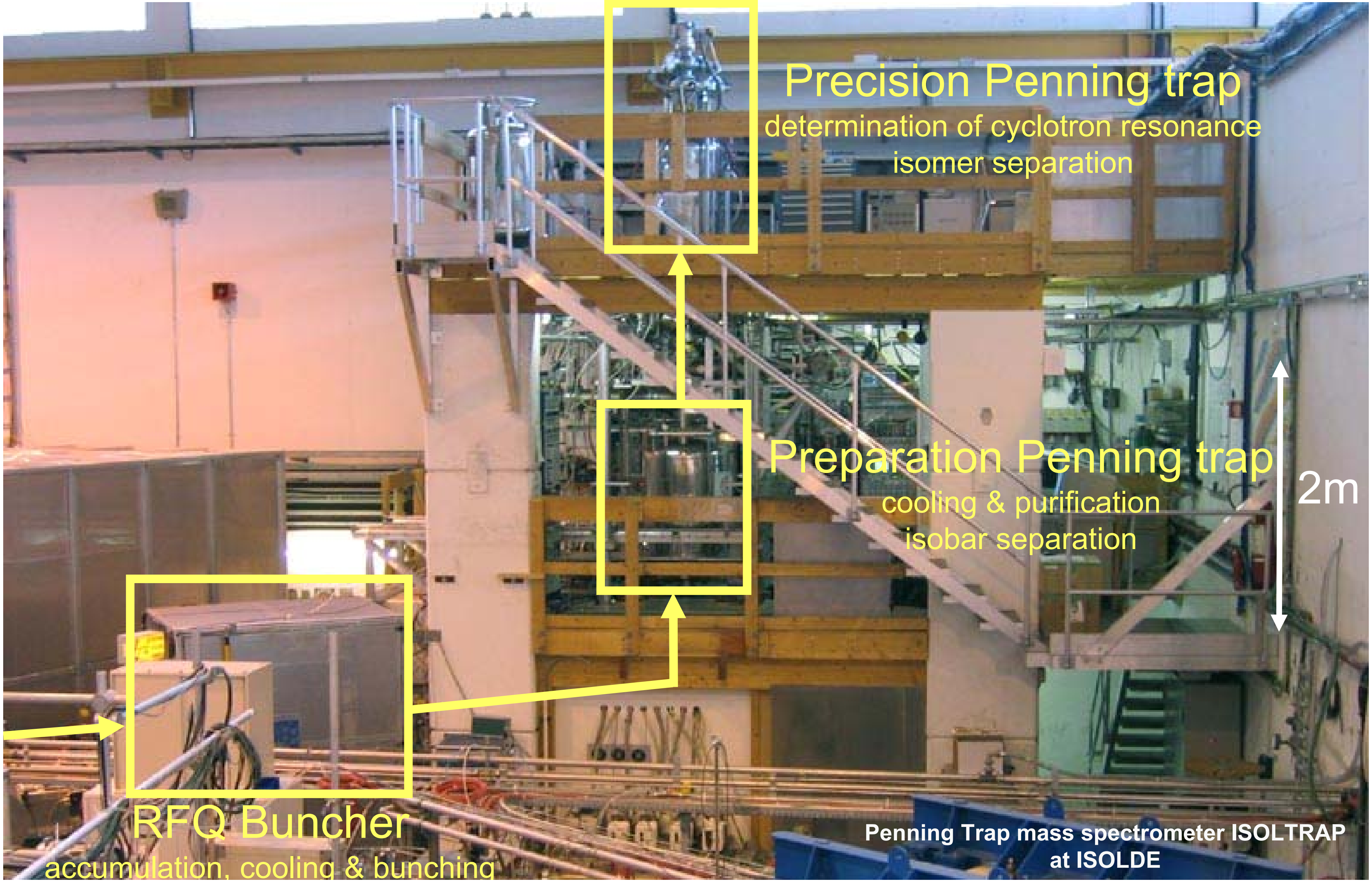
PRL 99, 252501 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

Nuclear Charge Radius of ^{8}He

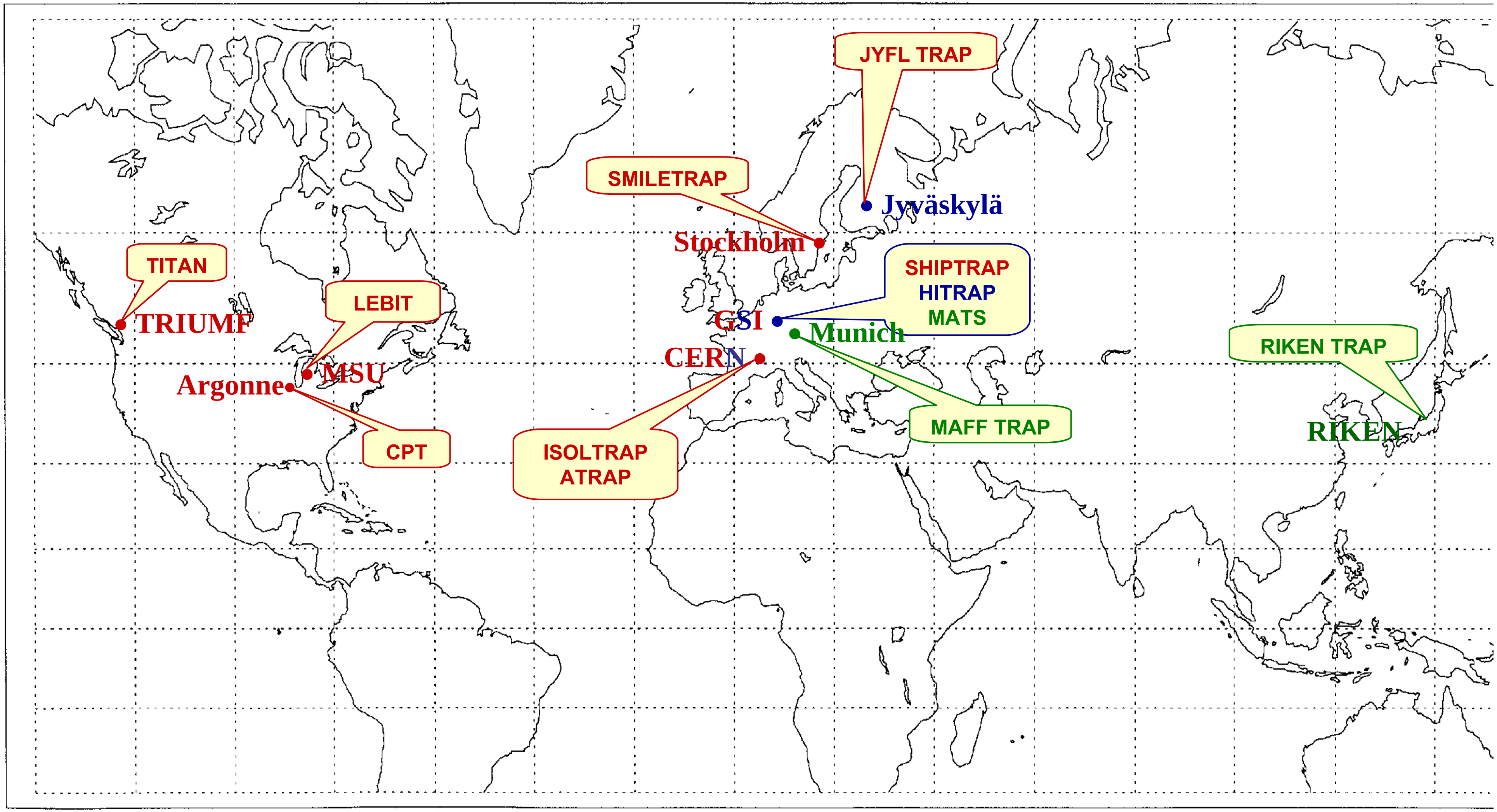
P. Mueller,[1,*] I. A. Sulai,[1,2] A. C. C. Villari,[3] J. A. Alcántara-Núñez,[3] R. Alves-Condé,[3] K. Bailey,[1] G. W. F. Drake,[4] M. Dubois,[3] C. Eléon,[3] G. Gaubert,[3] R. J. Holt,[1] R. V. F. Janssens,[1] N. Lecesne,[3] Z.-T. Lu,[1,2] T. P. O'Connor,[1] M.-G. Saint-Laurent,[3] J.-C. Thomas,[3] and L.-B. Wang[5]



Penning Trap Techniques for Mass Determination



Penning Traps at Accelerators for Mass Spectrometry

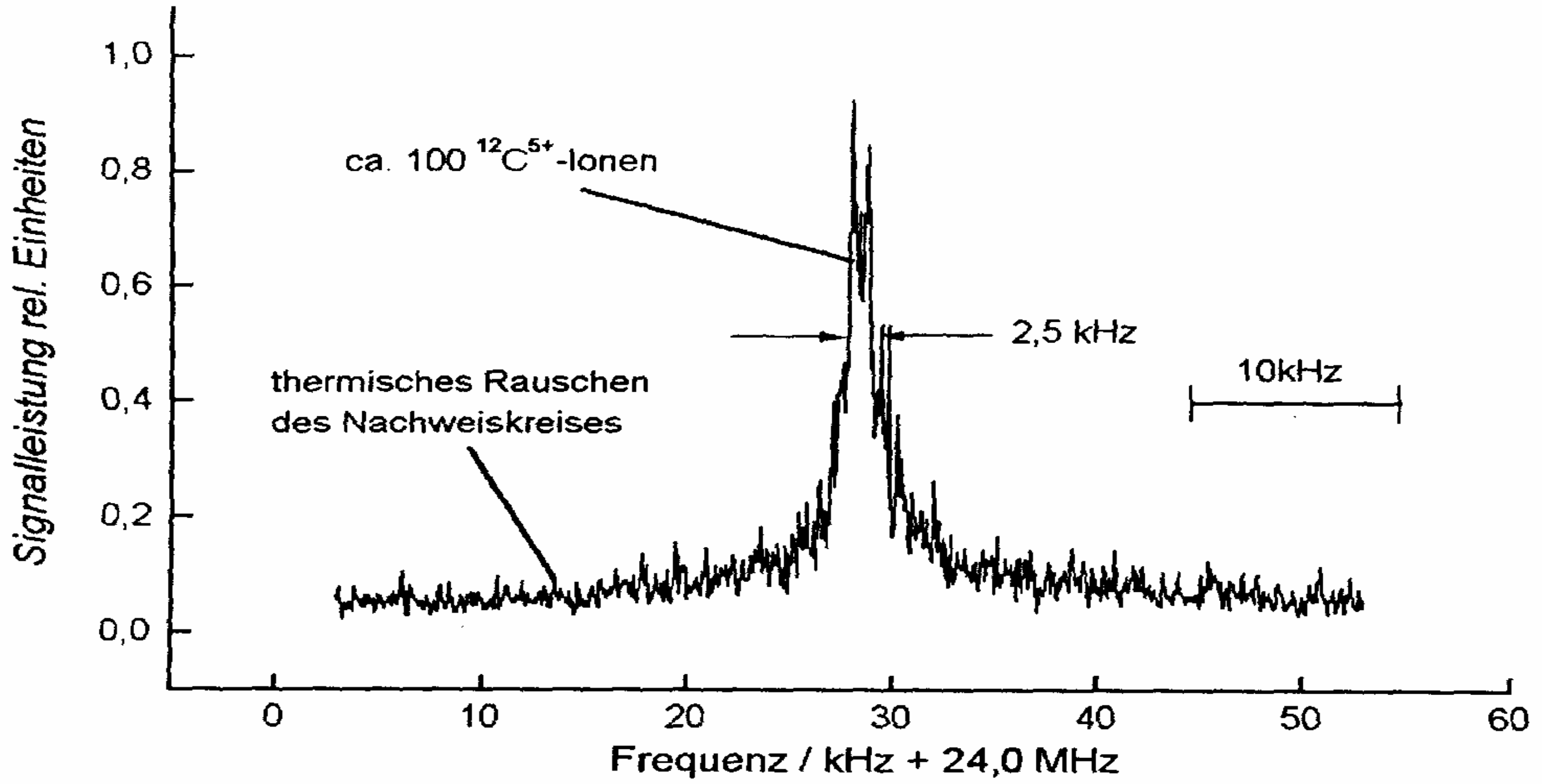


• operating facilities • facilities under construction or test • planned facilities

How Sensitive is Radiofrequency Spectroscopy in Traps?

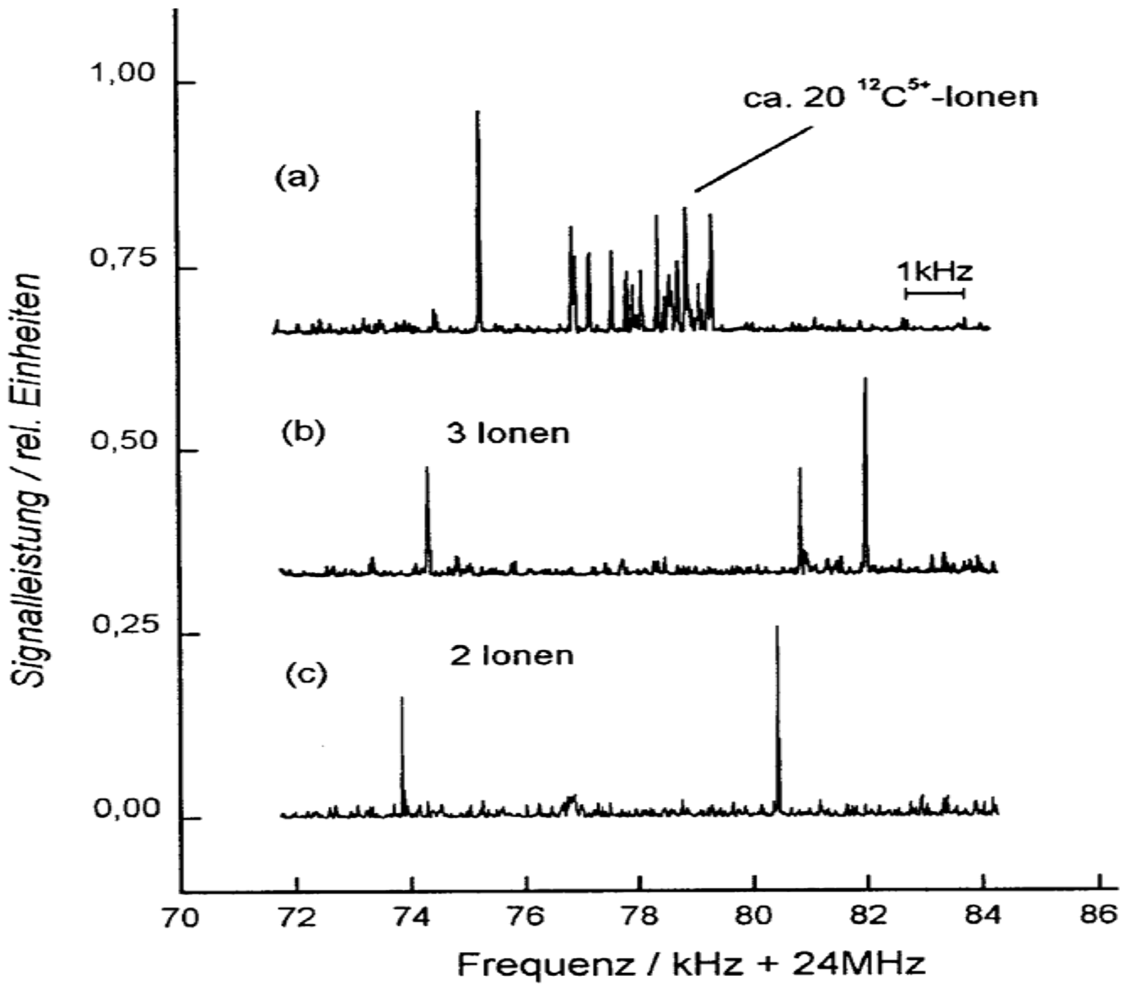
Cyclotron resonance signal of about 100 stored $^{12}C^{5+}$ ions

$$\Delta\nu_{FWHM} \approx 2.5\ \text{kHz}$$



How Sensitive is Radiofrequency Spectroscopy in Traps?

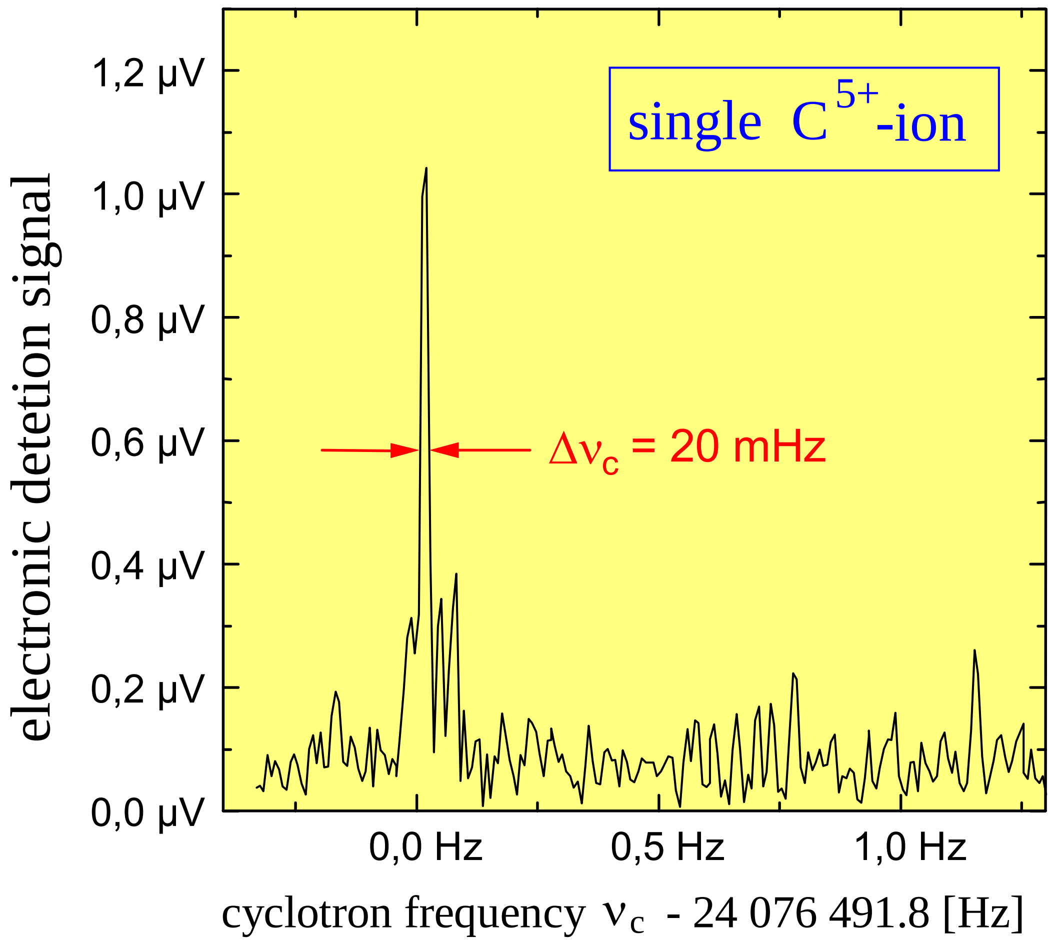
Cyclotron resonance signal of 20 - 2 stored $^{12}C^{5+}$ ions



How Sensitive is Radiofrequency Spectroscopy in Traps?

Cyclotron resonance signal of a single $^{12}C^{5+}$ ion

$\Delta\nu_{FWHM} \approx 20$ mHz -> $R = 10^9$



How Sensitive is Radiofrequency Spectroscopy in Traps?

Coulomb interactions and relativistic shifts cause line broadening:

With 100 ions present in the trap, the resolving power is only 10^4.

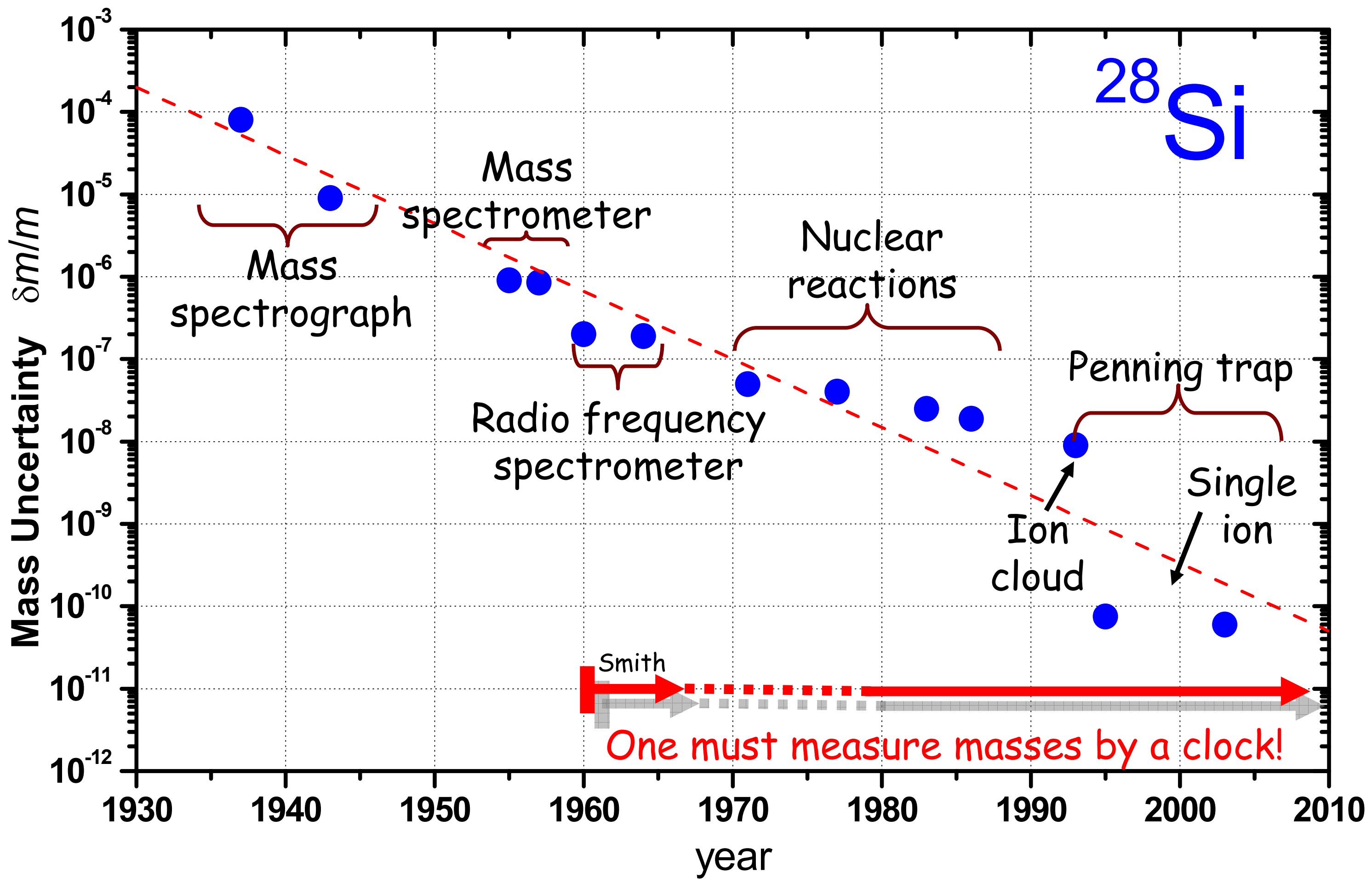
With one ion present in the trap, a resolving power of 10^9 is achieved.

Cooling is required for eliminating relativistic mass shifts.

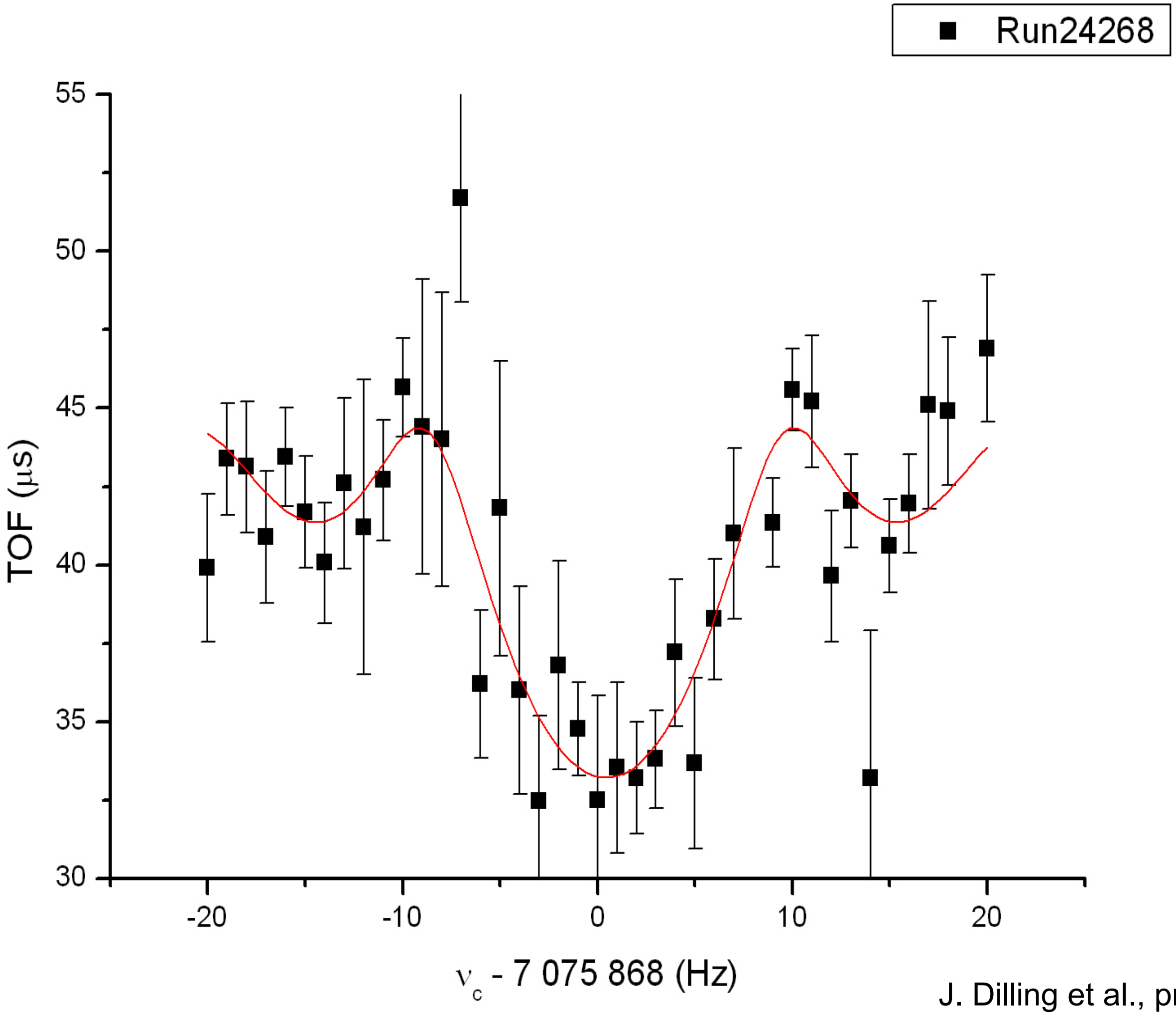
By performing the experiment with only one ion distortions by Coulomb interaction are avoided.

Radiofrequency spectroscopy has single-ion detection efficiency.

The Increase of the Accuracy of Mass Spectrometry

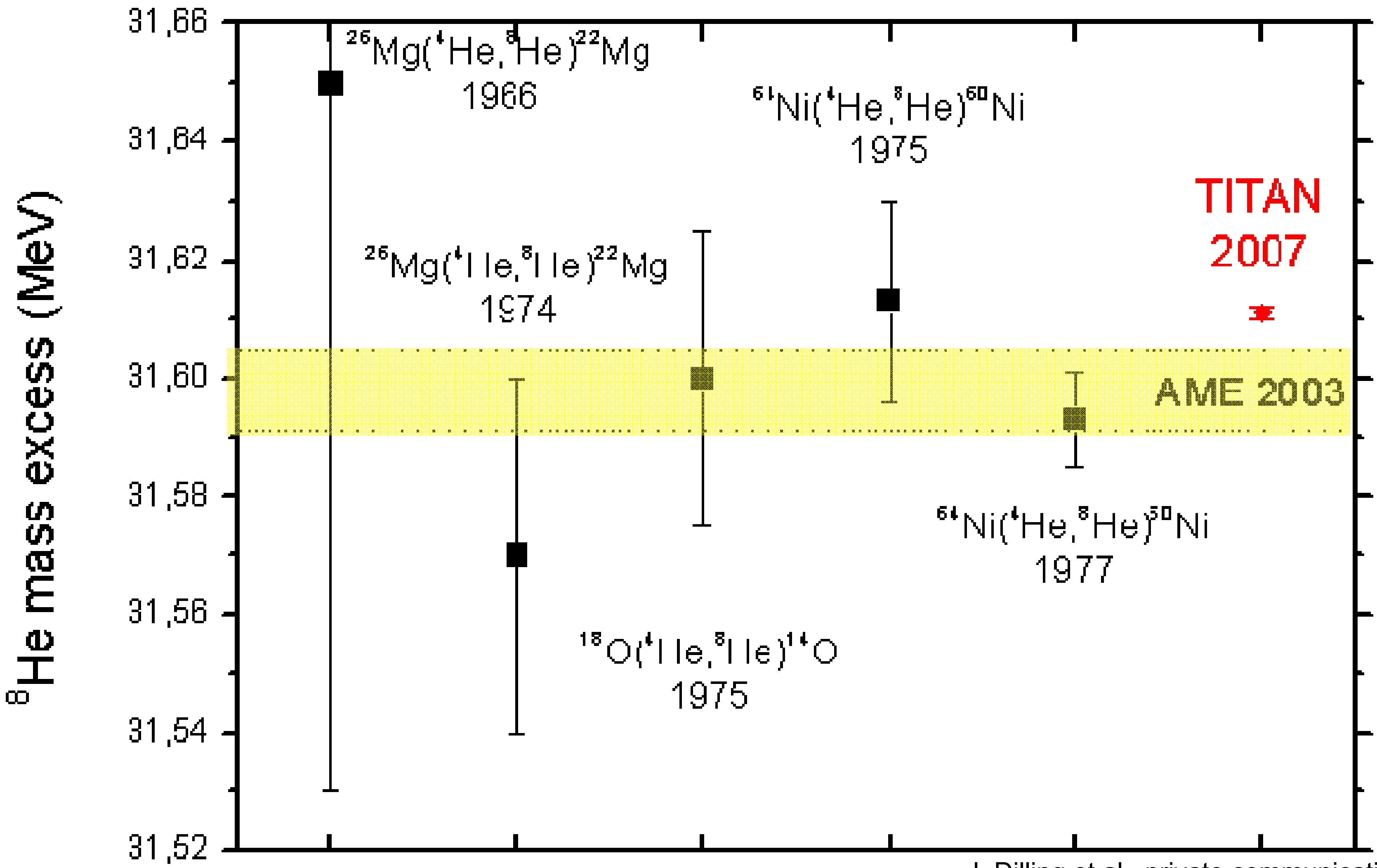


Mass Measurement of Helium-6 at TITAN @ TRIUMF November 2007



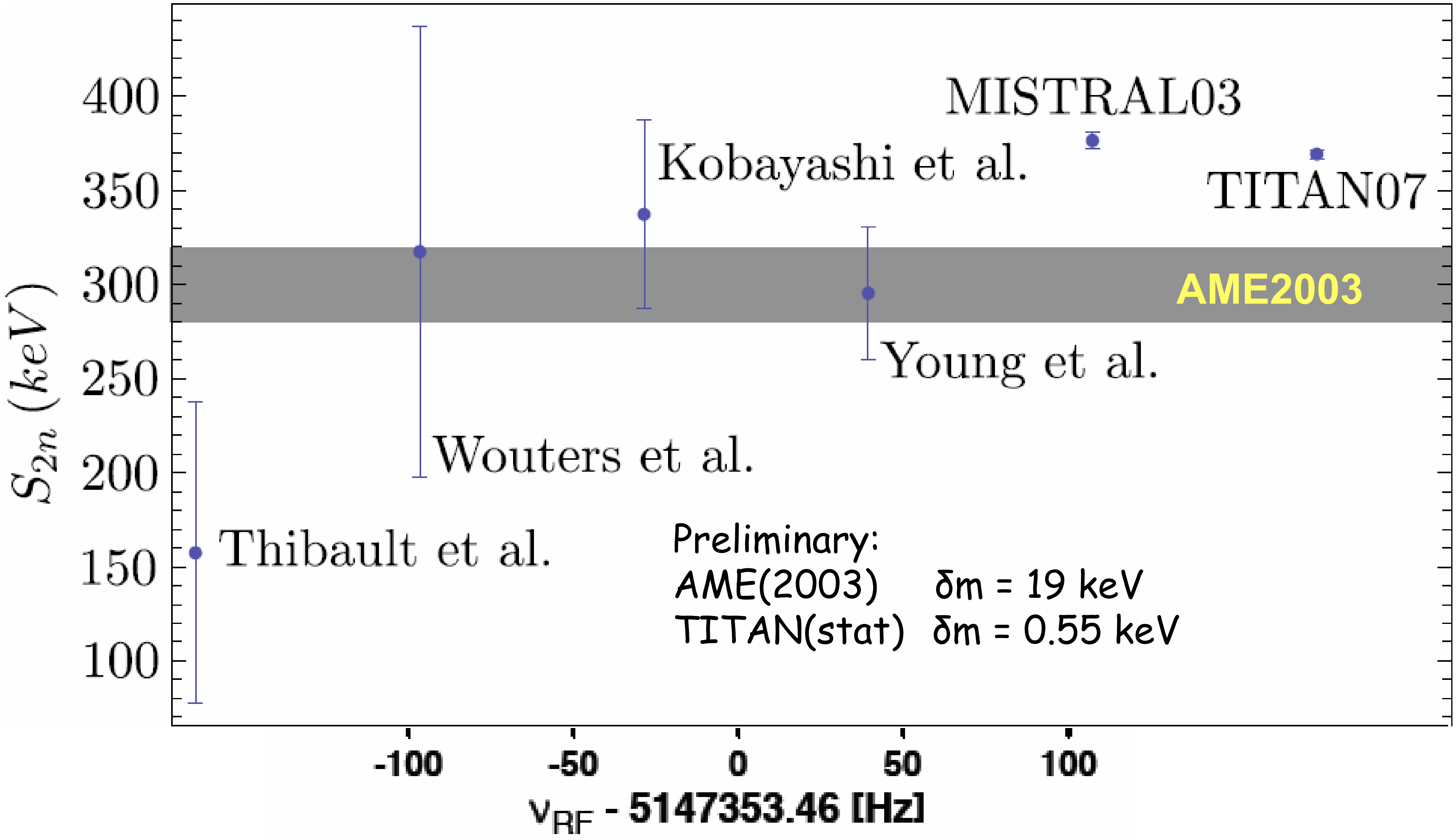
J. Dilling et al., private communication

Mass Measurement of Helium-6 at TITAN @ TRIUMF November 2007



J. Dilling et al., private communication

Mass Measurement of Lithium-11 at TITAN @ TRIUMF December 2007



J. Dilling et al., private communication

An Appeal to the Theoreticians

Theoreticians should try to fit all model-independent properties at the same time (spin, magnetic moment, quadrupole moment, charge radius and binding energy), and not separately as it is usually done.

Presently, each nuclear property of the lithium isotopes is reproduced best by a specific, but different theory.

The lithium isotopes should be good testing objects for theory.

There is another model independent quantity
which is very difficult to determine:

the hyperfine anomaly

But the experimental effort makes only sense if
theoreticians really try to predict it.

High-Accuracy Measurement of Magnetic HFS Spitting and g_I in Traps – Hyperfine Anomaly

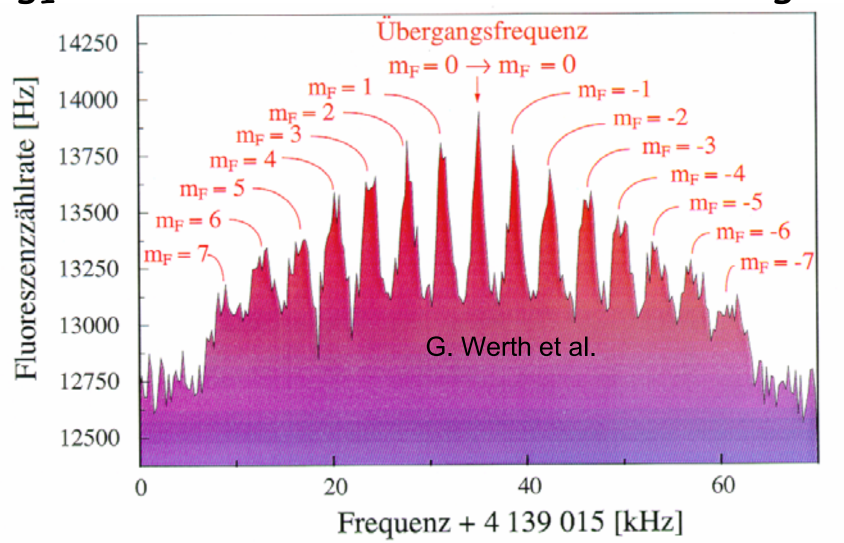
Bohr-Weisskopf effect: $A = A_{point}\,(1+\varepsilon_{BW})$
change of magnetic hfs interaction due to finite nuclear size

hyperfine anomaly: $\;{}^1\Delta^2=\{(A_1/g_1)/(A_2/g_2)\} - 1 \sim \varepsilon_1 - \varepsilon_2$
change of distribution of nuclear magnetism between two isotopes

For an experimental accuracy for the hyperfine anomaly ${}^1\Delta^2$ of about 10^{-2} - 10^{-4} the A-factor and g_I must be determined with an accuracy of about 10^{-5} –10^{-6} .

This is possible but very demanding.

g_I determination of Eu-148 in a Penning trap



A-factors: 10^{-12} in Paul traps
g_I-factors: $5{\cdot}10^{-7}$ in Penning traps

Where are the Limits?

The (extreme) halo nucleus lithium-11defines the present boundary conditions:

Very short half-life:	9 ms
Very small volume effect of IS:	30 kHz relative to ^{6}Li
Very large mass effect of IS:	11 GHz relative to ^{6}Li
Very small magnetic HF interaction:	900 MHz
Very small electric HF interaction:	22 KHz
High cyclotron frequency (q/m = 0.3)	6 MHz

Production yield:

1,000/s at ISOLDE	(1.6 µA 1.4 GeV protons)
30,000/s at TRIUMF	(40 µA 0.5 GeV protons)
~100,000/s at MYRRHA	(100-200 µA 0.5 GeV protons)

What will be Accessible at a MYRRHA ISOL Facility?

Atomic physics experiments are able to deal with 1 ion at a time.

A production yield of 1 ion per second is sufficient for atomic physics experiments.

All radionuclides available at ISOL facilities can be investigated by atomic physics techniques, even those with the shortest half-life.

Of course, long beam times are required at yields approaching 1 ion/s or below.

A dynamic range of about 5 orders of magnitude corresponds to up to about 5 isotopes at the steep slopes on the neutron-rich and neutron-deficient side of the production curve.

Some Remarks

An optical experiments is special for each elements. To prepare the atom or ion for an ambitious experiment is a lot of work and takes time. Examples: The development of the technique to measure the charge radii of lithium isotopes took 7 years. This is the time scale also for other precision experiments (antihydrogen, WITCH, EDM, parity, Fr, Ra, …..)

Atomic physics experiments can be prepared in most cases by use of stable isotopes at the home laboratory. However, some essential features (signal-to-background, systematic errors) can only be checked on-line.

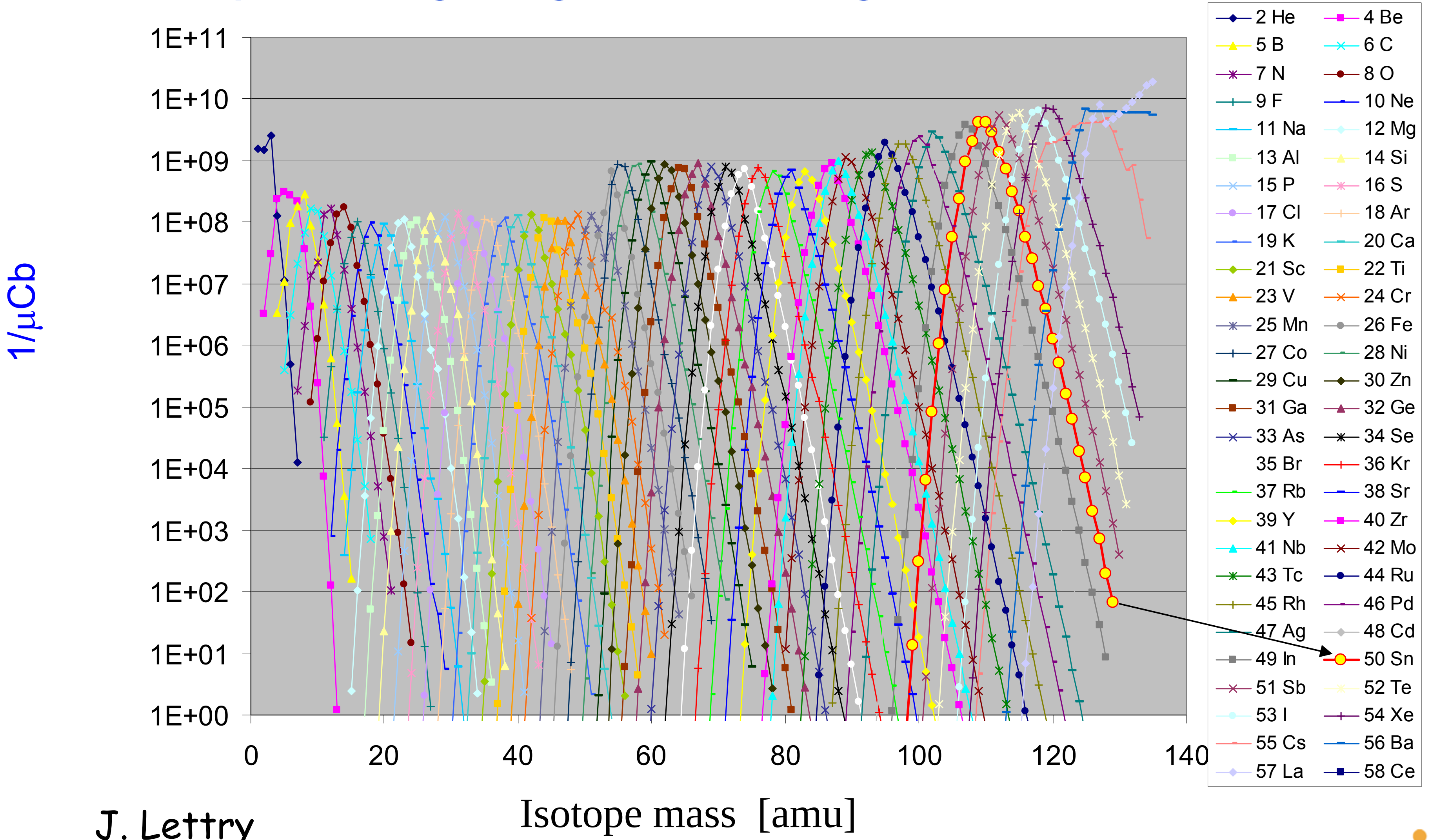
Alkali atoms confined in laser traps for neutral atoms and alkali earth ions confined in Paul and Penning traps will be a good starting point for MYRRHA. For example, Be-14 will be produced in reasonable amounts (100 ions/s at MYRRHA).

Not primarily produced isotopes can be investigated by letting the mother nucleus decay as, for example, in the case of the COMPLIS experiment: Hg – Au – Pt – Os

Still, a laser ion source should be foreseen. Solid state lasers are reliable

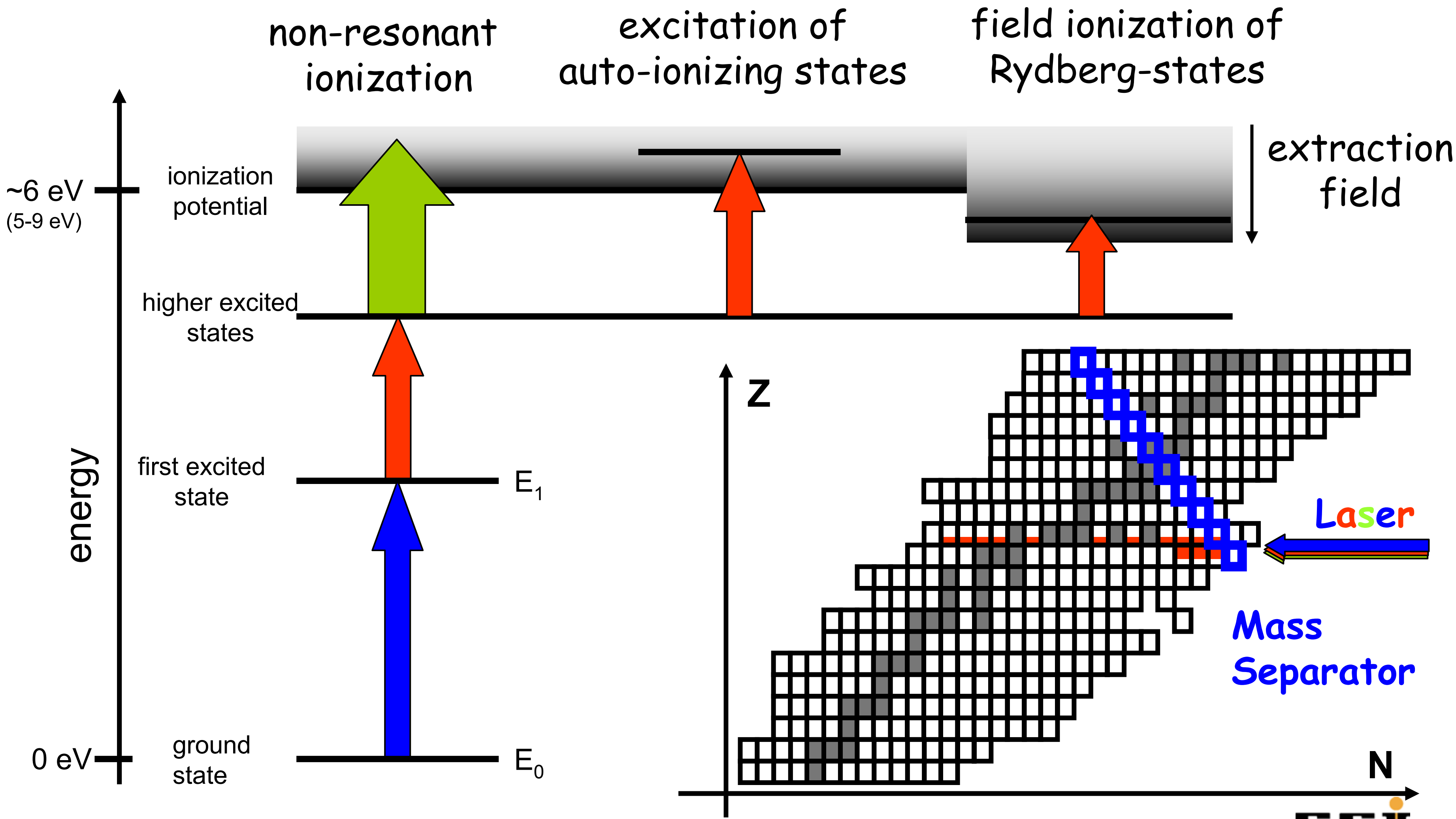
The Problem of Isobaric Contamination

1 GeV p + LaC target 10 g/cm^2 Silverberg & Tsao Production rates

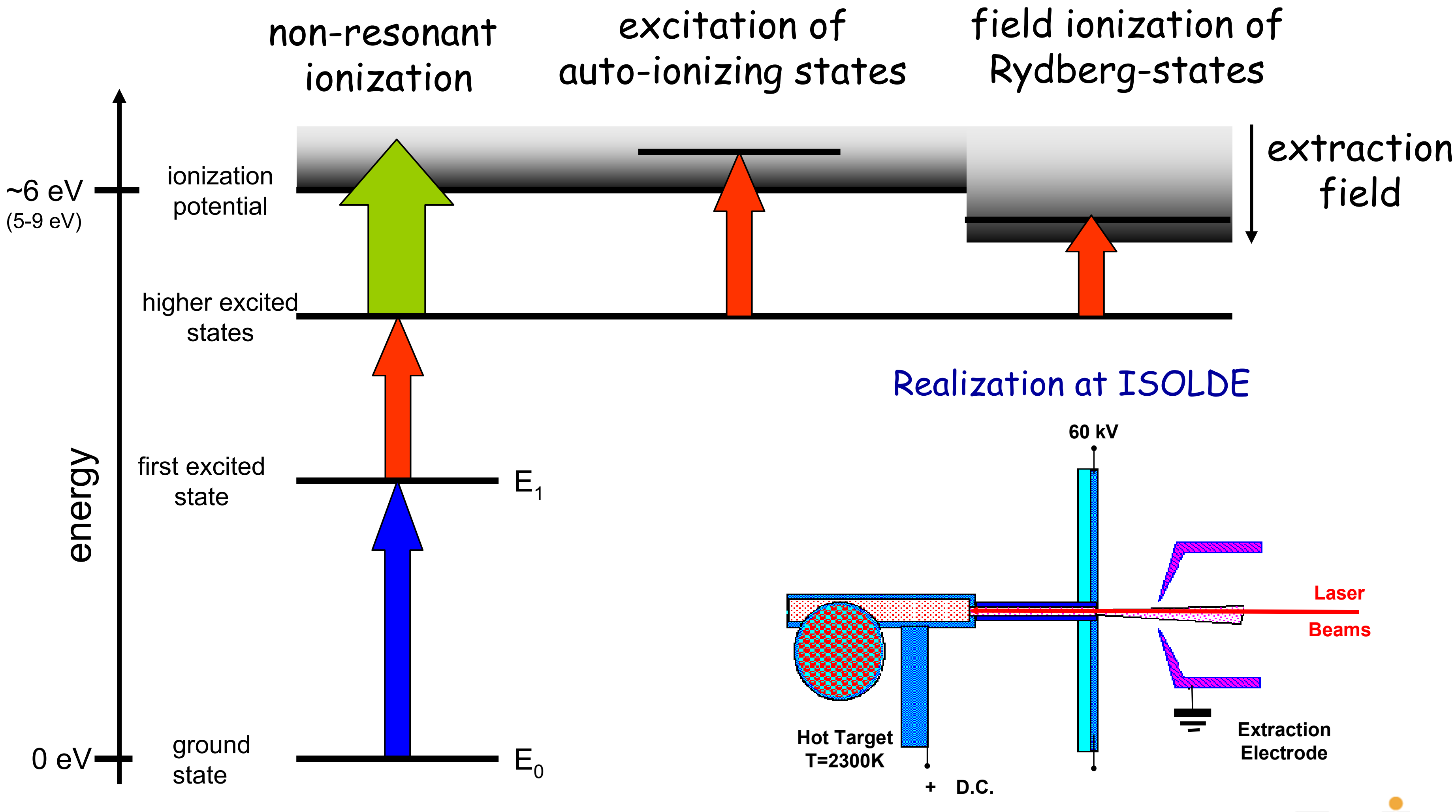


J. Lettry

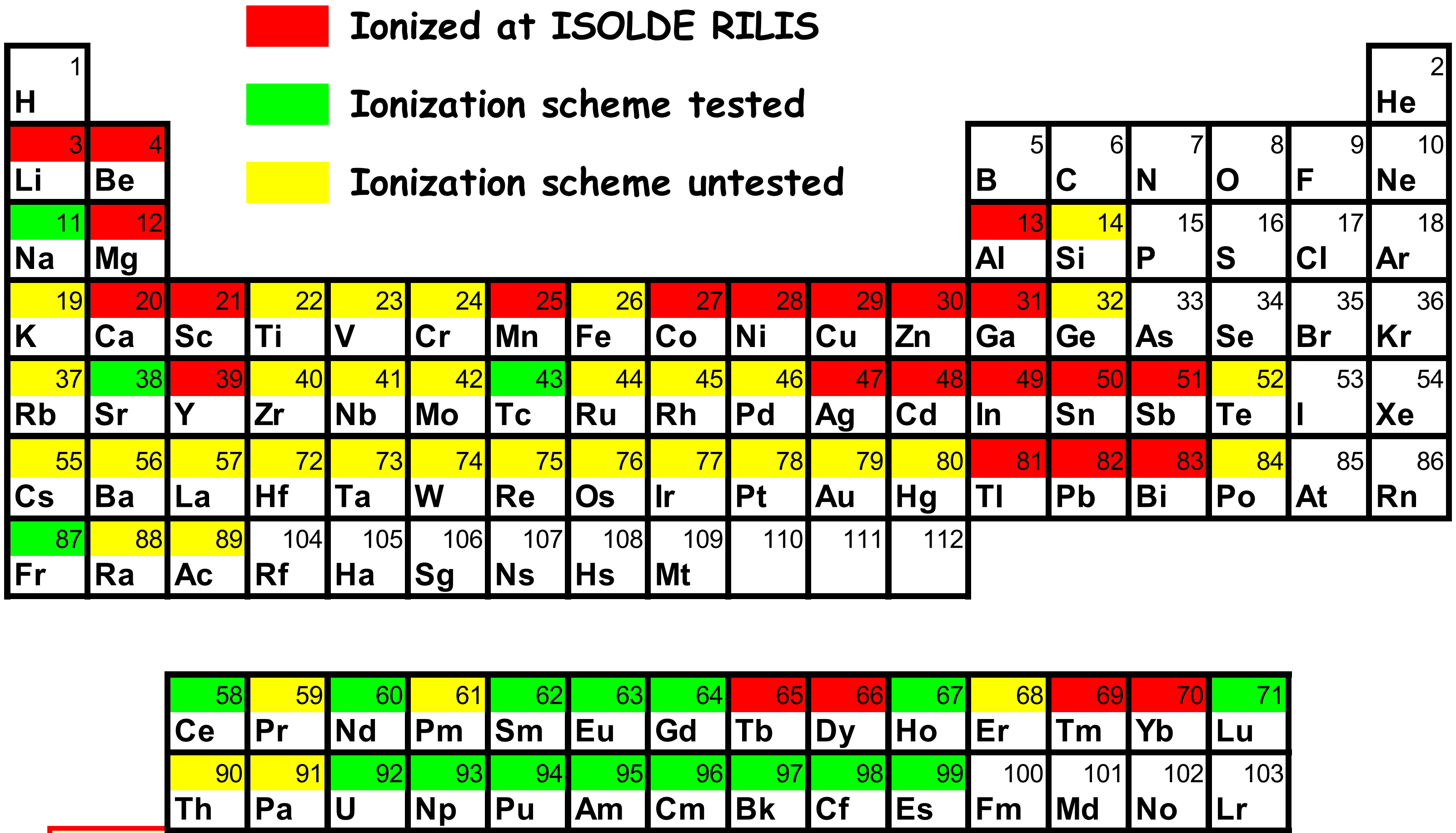
Resonance Ionization Mass Spectroscopy



Resonance Ionization Mass Spectroscopy



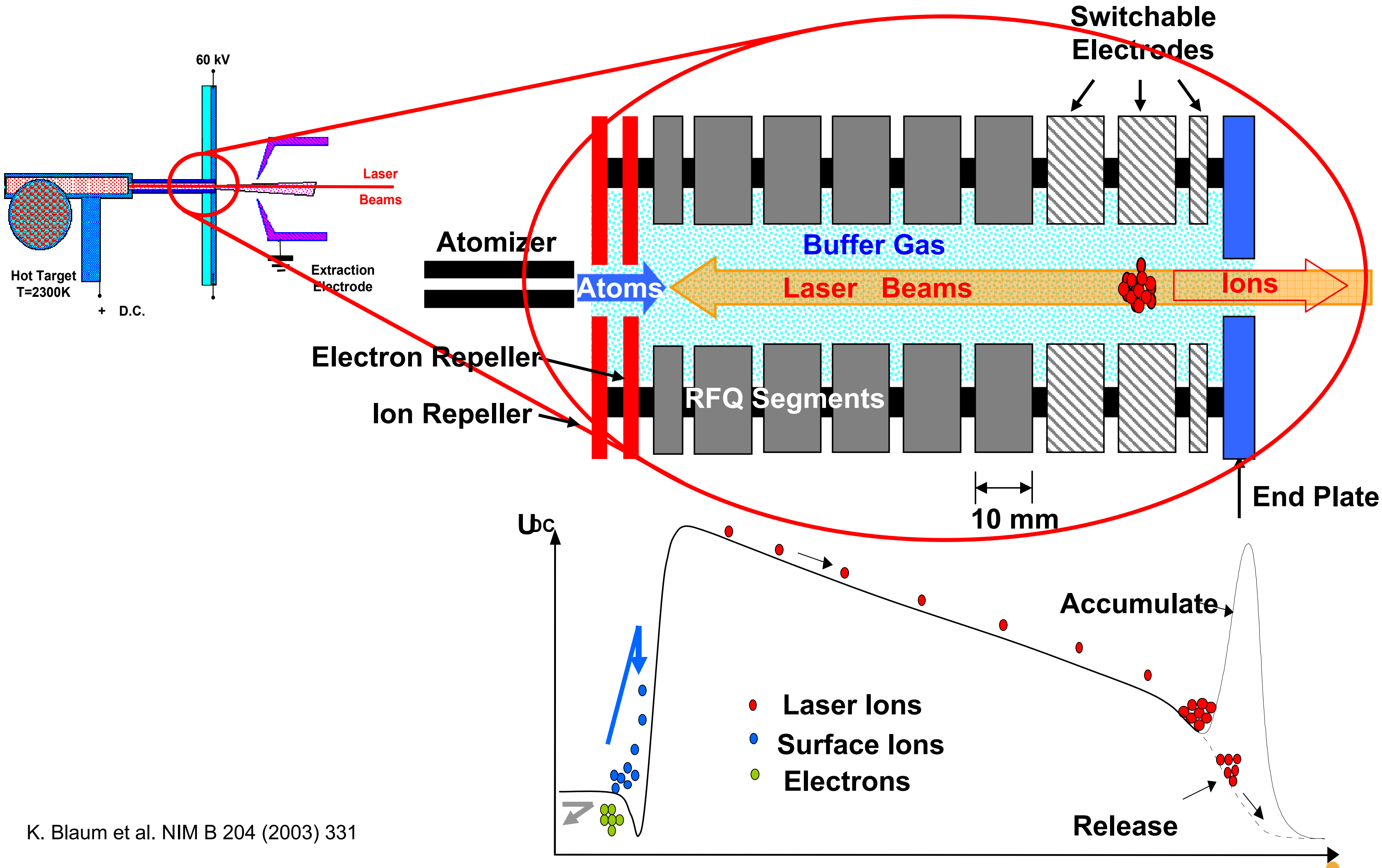
RIMS Schemes for ISOLDE



The laser ion source is used in more than 50 % of the beam time. But .....

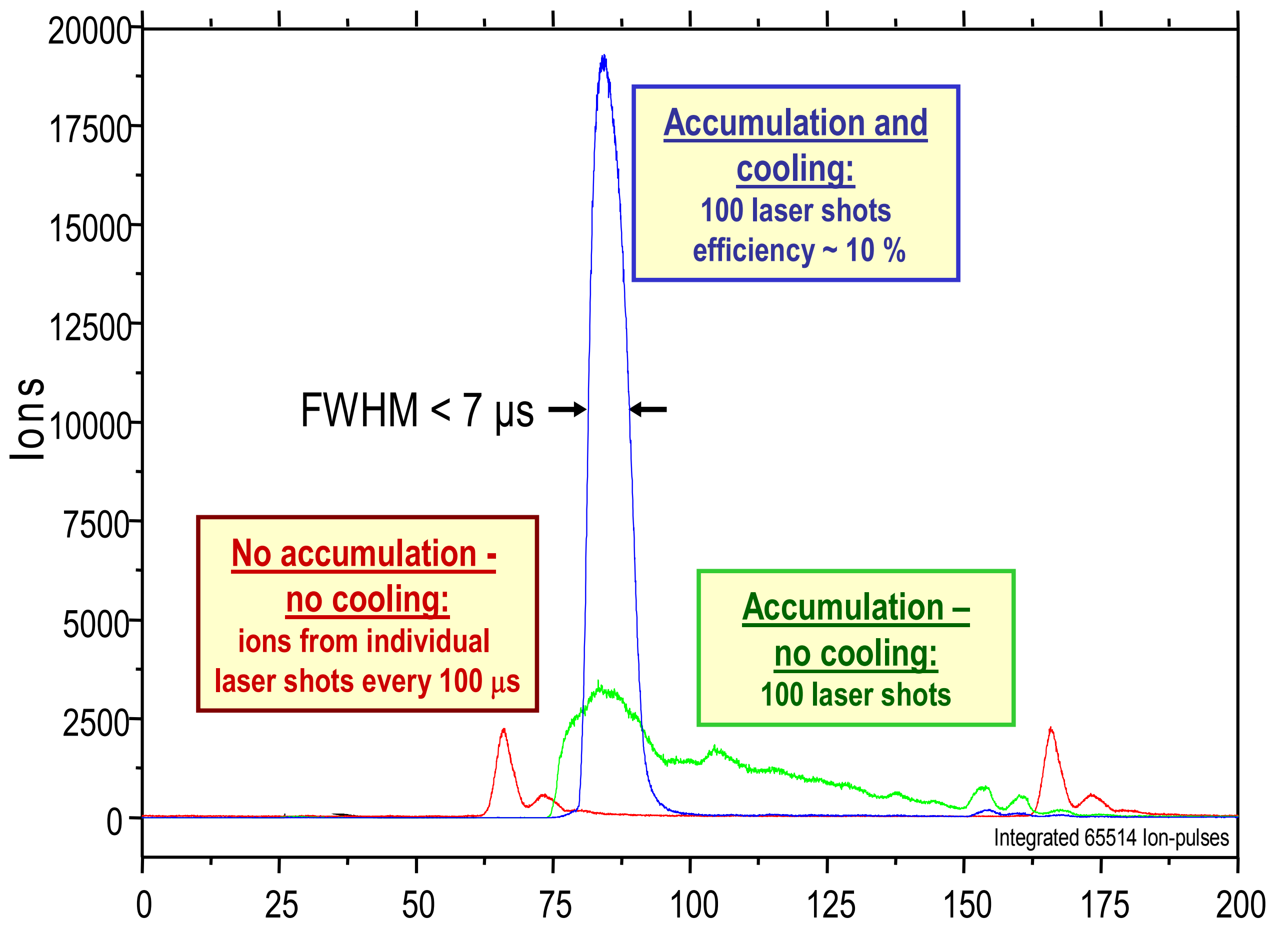
there is very often at ISOLDE a contamination by isobars which are surface-ionizable.

Fighting Isobaric Contamination with LIST (Laser Ion Source Trap)



K. Blaum et al. NIM B 204 (2003) 331

Ionization of Gallium Atoms in the LIST



First off-line demonstration at Mainz (Klaus Wendt et al.,)

Development going on at Mainz, Jyväskylä and TRIUMF

Efficient and highly selective ionization

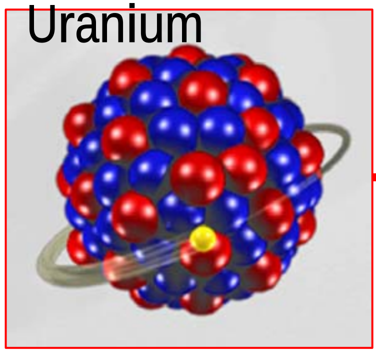
Suppression of isobars

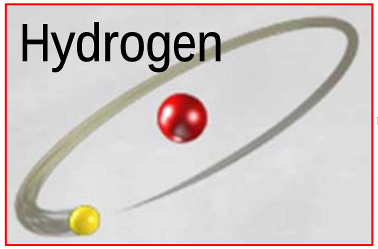
DC and bunched beams with low emittance

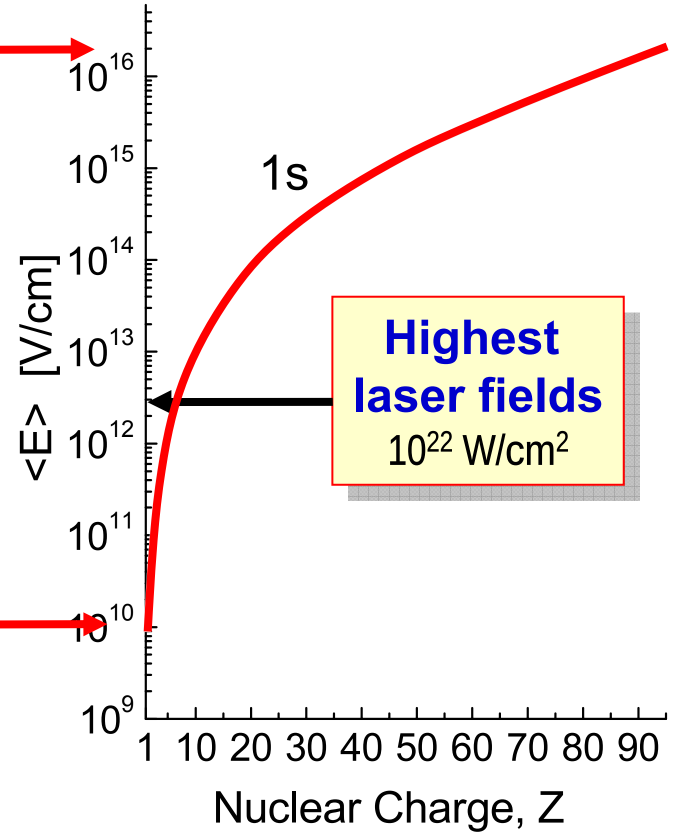
Polarized radioactive ion beams by optical pumping

K. Brück, C. Geppert, F. Schwellnus, K. Wies, K. Wendt

Test of Quantum Electrodynamics in Extreme Electromagnetic Fields and Spectroscopy of Simple Systems







Highest laser fields
10^{22} W/cm^2

H-like Uranium
$\langle E \rangle = 1.8\times10^{16}$ V/cm
$E_K = -132\times10^3$ eV
$\Delta E_{Lamb} \approx 500$ eV
$Z\cdot\alpha \approx 1$

***Q**uantum **E**lectro-**D**ynamics*

Hydrogen
$\langle E \rangle = 1\times10^{10}$ V/cm
Ek = -13.6 eV
$\Delta E_{Lamb} \approx 10^{-5}$ eV
$Z\cdot\alpha \approx 10^{-2}$

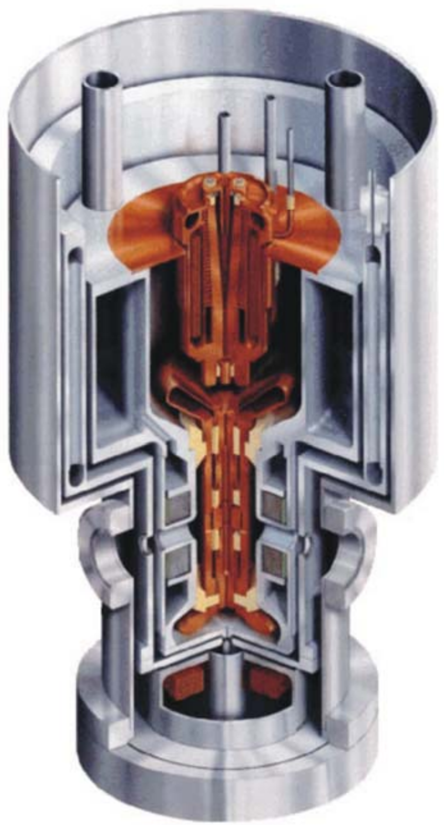
Experimental Challenges for Highly Charged Ions at Extremely Low Energies

- highly charged ions of stable and radioactive isotopes
- atomic ollisions at very low velocities
- surface studies and hollow-atom spectroscopy
- laser spectroscopy of hyperfine splitting in hydrogen-like ground state
- x-ray spectroscopy of Lamb shift
- diamagnetic correction
- g-factor measurements of the bound electron
- fundamental constants: fine structure constant, mass of the electron
- mass measurements of extreme accuracy
- calibration of hyperfine fields in simple systems
- calibration of $\Delta|\psi(0)|^2$ for isotope shift measurements
- polarization of radionuclides
- decay spectroscopy of highly-charged radionuclides

Production of Highly Charged Ions

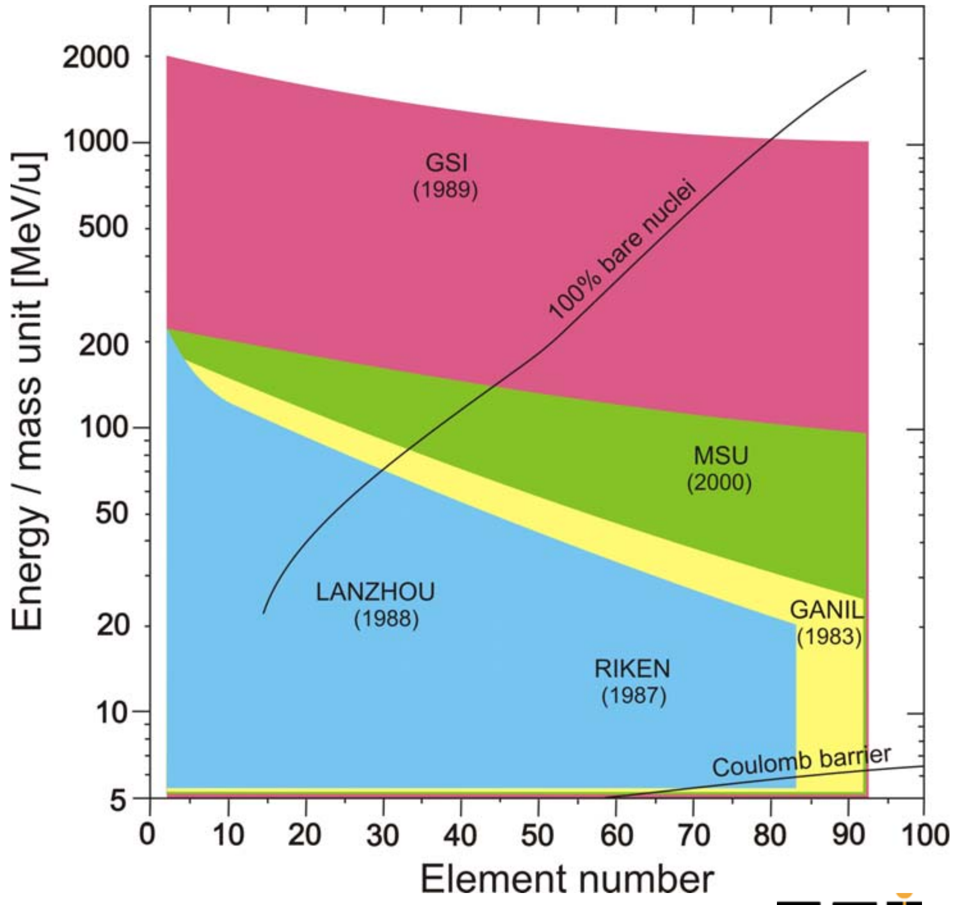
Ionization by highly energetic electrons

Electron Beam Ion Trap (EBIT)



Ionization of highly energetic ions passing a target

Heavy Ion Accelerator GSI at Darmstadt



Principle of the g-Factor Determination of the Bound Electron

cyclotron frequency

is the revolution frequency of a charged particle in an external magnetic field *B*: Lorentz force and centrifugal force are equal.

$$\omega_c = \frac{q_{ion}}{M_{ion}} B$$

Larmor frequency

is the precession frequency of a magnetic moment in an external magnetic field B. It equals the frequency required for flipping the spin.

$$\omega_L = g \frac{e}{2m_e} B$$

$$\Rightarrow \quad \omega_c << \omega_L \quad \Rightarrow$$

no gain of 3 orders of magnitude as in the case of the free electron

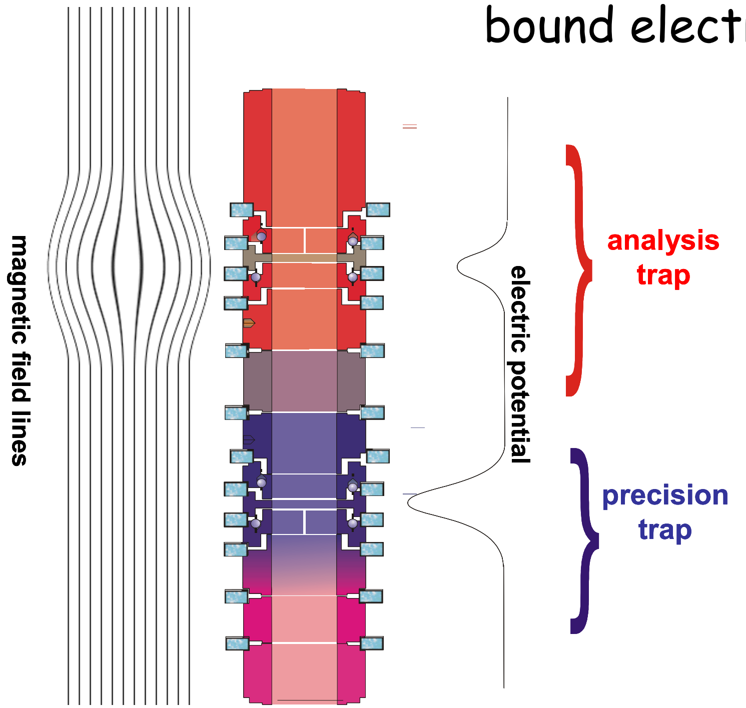
$$g = \left(\frac{\omega_L}{\omega_c}\right) \cdot \frac{\left(\frac{q}{M}\right)_{ion}}{\left(\frac{e}{m}\right)_e}$$

Set-Up for g-Factor Determination of the Bound Electron in a Single H-Like Ion

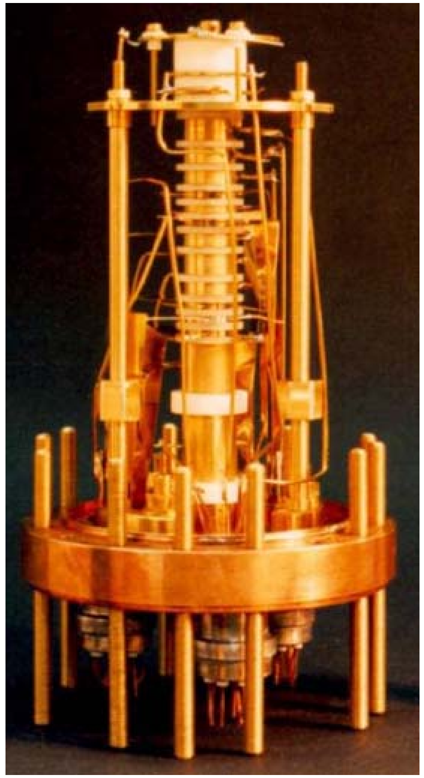
- two Penning traps:

  precision trap: homogeneous magnetic field for measurement of B via determination of the cyclotron frequency of a single ion and induction of spin flips

  analysis trap: inhomogeneous field for detection of spin direction of the bound electron



GSI – University of Mainz collaboration



- LHe temperature:
  - single-ion detection
  - small amplitudes
  - extreme ultra-high vaccum
  - long storage time

- superconducting magnet:
  - high frequencies
  - high stability
  - high accuracy

Nuclear Moments and Charge Radii from Measurements of the g-factor of the Bound Electron

NUCLEAR MAGNETIC MOMENT

$$g_F = g_J \frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)} - g_I \frac{F(F+1)+I(I+1)-J(J+1)}{2F(F+1)}$$

theory 10^{-9}

experiment 10^{-9}

$\Rightarrow$ **10^{-6}**

For the first time:
check of diamagnetic correction

NUCLEAR CHARGE RADII

$$\Rightarrow \quad \Delta g_{AA'} \cong A(Z\alpha)\delta\left\langle r^2 \right\rangle_{AA'}^{1/2}$$

To lowest orders,

$$\Delta g = \frac{8}{3}(\alpha Z)^4 \langle (r/\lambda\!\!\!^{-}_C)^2 \rangle \times \left[1 + (\alpha Z)^2 \left(2 - \Gamma - \frac{\langle r^2 \log(2\alpha Z r/\lambda\!\!\!^{-}_C) \rangle}{\langle r^2 \rangle} \right) \right]$$

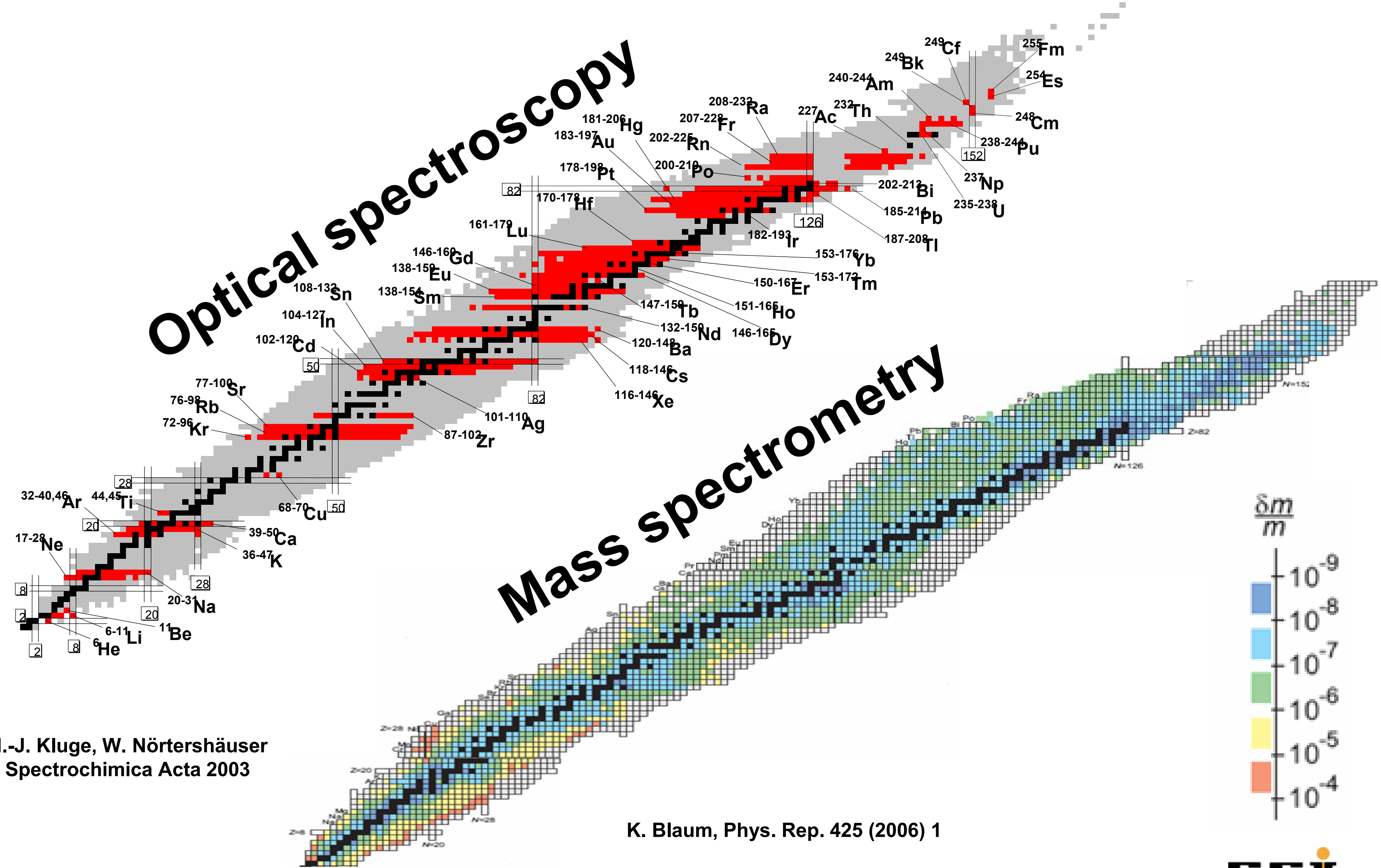
(Glazov and Shabaev, 2001)

Glazov and Shabaev, PL A297 (2002) 408

Exact calculations are possible!

Is there an idea for decay studies of 100% polarized hydrogen-like ions, that are backing-free stored in a trap, cooled to 4 K and where the beta particles are guided by the magnetic field to detectors?

Laser Spectroscopy and Mass Spectrometry in Long Isotopic Chains



H.-J. Kluge, W. Nörtershäuser
Spectrochimica Acta 2003

K. Blaum, Phys. Rep. 425 (2006) 1

Summary

Atomic physics techniques are

- accurate
- sensitive and
- deliver model-independent information on nuclear ground state properties.

Laser spectroscopy is (still) the only access to charge radii of short-lived isotopes.

Now, also the charge radii of very light nuclei are accessible. In this case, atomic theory is essential.

Masses deliver information on all forces acting in the atom except gravitation. They are essential in many areas of science (nuclear structure, CVC, neutrino mass, QED, …).

Resonance ionization (mass) spectroscopy is beside co-linear spectroscopy the most often applied laser spectroscopic technique at radioactive beam facilities.

Laser ion sources are based on RIMS. They offer efficiency, reliability and isomer selectivity. Combined with bunching and cooling of ion beams in a segmented, gas-filled radiofrequency quadrupole trap, the laser ion source trap (LIST) will solve the problem of isobaric contamination.

Highly charged ions are used to test QED in extreme electromagnetic fields. Using different charge states of the same isotope, nuclear-size effects can be made insignificant. If QED is found to be valid, nuclear effects in simple few-electron (radioactive) ions can be measured and safely treated by atomic theory.

Leave space for an laser ion source and an electron beam ion trap as a charge breeder,